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Optimal thermal storage operation strategies with heat pumps and solar collector

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Energy consumption inside of building plays a key role occupying as 30-40% by the data of United Nations Statics Division (UNSD). Energy efficient building with light, medium and massive type discusses for designing the high efficient system component inside of building model. Control strategy between two tanks and solar collector completes the task by the Matlab codes and building simulation software. Result compares with the Pareto Efficiency curve for achieving the energy saving component and low cost operation.

In this thesis, to achieve the goal of energy strategy and get the higher efficiencies of building energy, most common building type of single family house (light, medium and massive type) is suggested to renovate the energy system of the house. The domestic hot water consumption and space heating heat demand is the main target to satisfy the energy need in the house, two geothermal heat pumps and two thermal tanks with one solar collector studies for the respond of the energy requirement.

Simulation software, IDA ICE (version 4.7.1) employs for the energy-utilized data set and Matlab studies for the control and the optimization result. IDA ICE can generate one tank model with one heat pump and solar collector, in the scope of the two tanks and two heat pumps model, one tank model is made separately only for the usage of domestic hot water consumption and the other is made only for the space heating. After producing two tanks model separately named as high temperature tank and low temperature tank, both combine with the Matlab software for the control strategy and optimization.

To make the result after the control of the system components, energy balance equation and Artificial neural network (ANN) introduces. ANN is required for making the structure of the heat demand of solar collector and heat pump. Multi objective optimization presents and non-dominant sorting genetic algorithm (NSGA II) shows the Pareto Front of the result. Pareto Front is the optimal selection of the tank size and solar collector area by using the two different objective functions. One is annual heat pump energy usage and the other is operating cost of components considering Life Cycle Cost (LCC).

Validation conducts with one tank model. One tank model in medium type of building is chosen for validation and comparing the result with the IDA and MOBO (Multi-Objective Building Performance Optimization) together. MOBO is optimization software possible to find suitable decision variables in the huge number of possible combinations, which let achieve defined conflicting objective functions and satisfy specified constraint functions. Validation turns out tank model with Matlab and ANN with NSGA II generates same pace of IDA ICE and MOBO combination later on.

Keywords: Ground source heat pump, energy simulation, multi objective optimization, IDA-ICE, Solar collector, artificial neural network, NSGA II

Preface

This master thesis conducts based on the academic courses of the theoretical modelling of HVAC systems and models and optimization for heating and cooling of the building. Literature review comes into action previously concerning the control and prediction control for data based and model based model.

Space heating heat demand accounts for the main mode in Finnish households' ventilation system. Domestic hot water consumption follows the schedule of occupants' profile. Two storage tanks are considered and both connect separately with two heat pump systems for satisfying the requirements of ventilation and water consumption. In this thesis, two tank models generates from the IDA ICE, the building simulation software and Matlab together. In addition, multi-objective optimization studies based on the result data set with the non-dominant sorting genetic algorithm (NSGA II) method.

As the supervisor of the thesis, Professor Kalevi Ekman of Product Development at Aalto University is decided and as an instructor, Risto Kosonen, professor of HVAC Technology at mechanical engineering department is determined. Another instructor, Doctor Jyrki Kajaste helps me to guide the tank model. As a mechanical engineering department student, choosing product development as my major, I put more time to recognize the energy community and system components to do this thesis. Studying the field of control and connecting components inside of mechatronics part were useful to achieve the result of the thesis.

I appreciate professor Kosonen as my principal instructor to help all of this work and make time to guide me to write the thesis in the fast method. I also appreciate HVAC group researchers and doctoral degree students to help this work. Especially to Vahid Arabzadeh, Paula Sankelo and Juha Jokisalo. I thank to the Mika Vuolle and Erkki Karjalainen the staffs of Equa Company to send me software packages of IDA-ICE and MOBO, building simulation and the optimization software.

I really appreciate this opportunity to finish this thesis

Thanks.

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Nomenclature

a'_n		Present value factor of annual maintenance cost
a''_n		Present value factor of annual energy cost
A_c	[m^2]	Collector area
A_{panel}	[m^2]	Surface Area of Panel
α		Absorption coefficient of plate
C_i	[J/kg*K]	Specific heat of indoor air
C_m	[J/kg*K]	Specific heat of building structure
C_p	[J/kg*K]	Specific heat of water
COP_C		Carnot COP for heat pump
COP_N		Nominal measured COP of heat pump
COP_T		Hourly theoretical COP
DHW_a	[m^3/m^2 a]	Total annual specific consumption of domestic hot water
DHW(t)	[m^3/h]	Hourly consumption of domestic hot water
e		Escalation rate
e(t)		Error (set point – process variables)
Ene		Energy profit
f		Inflation rate
f(x)		Objective function or decision vector defined by the objective Functions
Fr		Solar-collector heat removal factor
$G_j(x)$		Inequality constraints
G_{mi}		Thermal conductance between materials and indoor air
G_{sm}		Material thermal conductance
G_{ven}		Thermal capacity of ventilation (AHU)
G_{win}		Thermal conductance of window
$H_k(x)$		Equality constraints

$h_{radiation}$	[W/m^{2}K]	Heat Transfer coefficient
i		Nominal interest rate
I	[W/m^2]	Solar radiation density to solar collectors
Inv		Investment cost for the sum of thermal solar-collector and Tank price
K_i		Integral gain, tuning parameter
K_p		Proportional gain, tuning parameter
M		Maintenance cost
$\dot{m}_s$		Mass flow of air
n		Holding period of investment
Q_{out}		Heating power of heat pump
$\dot{Q}_{AHU}$		Heat Power in the AHU
$\dot{Q}_{Convection}$		Heat Power from convection (φ_c)
$\dot{Q}_{Domestic}$		Heat Power inside of building
$\dot{Q}_{equipment}$		Internal heat gain from equipment
$\dot{Q}_{Heating}$		Internal heat gain from the coil of Air handling unit (AHU)
$\dot{Q}_{Heatpump2}$		Heat power from the heat pump connected to the low Temperature tank
$\dot{Q}_{Low\ temperature\ tank}$		Heat power from the low temperature tank
$\dot{Q}_{machine}$		Internal heat gain from machine
$\dot{Q}_{materials + air}$		Heat Power between materials and air
$\dot{Q}_{materials}$		Heat transfer in the material of the wall
$\dot{Q}_{people}$		Internal heat gain from people
$\dot{Q}_{radiation}$		Heat Power from radiation (φ_r)
$\dot{Q}_{Solar\ collector}$		Heat gain from the solar collector
$\dot{Q}_{window}$		Heat Power from window
$\dot{Q}_{zone}$		Heat Power in the building

r		Real interest rate
r_e		Escalated real interest rate
ρ		Density of air
s		Complex frequency
T_a		Ambient temperature
T_{a1}		Temperature inside of AHU coil
T_c		Collector average temperature
T_{con}		Condenser temperature
T_{eva}		Evaporator temperature
T_{fi}		Flat-panel inlet fluid temperature inside of solar collector (K)
T_{fo}		Flat-panel outlet fluid temperature inside of solar collector (K)
T_i		Indoor temperature
T_m		Temperature of the material node in the building structure
T_{mix}		Temperature in the mixing box
T_o		Temperature of outdoor air
T_s		Temperature of ventilation (AHU) supply air node
T_r		Room Temperature
$T_{panel\ air}$		Air temperature faced to the surface of the panel
$T_{surface}$		Surface temperature of the panel
T_{win}		Supply air temperature of AHU
T_{wout}		Exhaust air temperature of AHU
U	[W/m^{2}K]	Tank heat loss conductance
U_L	[W/m^2]	Solar collector heat loss coefficient
$W_{electric}$		Electricity consumption of heat pump
φ_{hc}		Space heating heat load
τ		Variable of integration
η_{AHU}		Efficiency of AHU

Abbreviation

ANN	Artificial Neural Network
BREEAM	Building Research Establishment Environmental Assessment Method
CAV	Constant Air Volume
CHP	Combined Heat and Power
CLO	Clothing insulation
COP	Coefficient of Performance
DH	District Heating
DHW	Domestic Hot Water
EA	Evolutionary Algorithm
EC	European Commission
EED	Energy Efficiency Directive
EER	Energy Efficiency Ratio
EPA	Environmental Protection Agency
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
ETS	Emission-Trading System
g-value	Total solar transmittance
GA	Genetic Algorithm
GBC	Green Building Council
GHG	Green House Gas
GSHP	Ground Source Heat Pump (Geothermal heat pump)
GUI	Graphical User Interface
HEPAC	Heating, Plumbing and Air Conditioning
HVAC	Heating, Ventilation and Air Conditioning
IC	Investment Cost
IDA ICE	IDA Indoor Climate and Energy
IEA	International Energy Agency

IFC	Industry Foundation Classes
LEED	Leadership in Energy and Environmental Design
LCC	Life-Cycle Cost
MET	Metabolic Equivalent
MOBO	Multi-Objective Building Performance Optimization
NBCF	National Building Code of Finland
NER300	New Entrant Reserve 300
NSGAII	Non-Dominant Sorting Genetic Algorithm II
nZEB	Nearly Zero Energy Building
PI	Proportional integral
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
REHVA	Federation of European Heating, Ventilation and Air Conditioning Associations
SBO	Simulation-Based Optimization
SPF	Seasonal Performance Factor
SEER	Seasonal Energy Efficiency Ratio
UNDP	United Nations Development Program
UNEP	United Nations Environment Program
VAV	Variable Air Vol

1. Introduction

1.1 Background

European commission occupies the executive body of European Union (EU), implementing decisions upholding the EU treats. In 2015, European commission leads the project of the Energy Union to manage the stable supply of energy in European market. The Energy Union is the modification of previous proposals of energy policies. Previous European energy policies are composed of short term and long-term energy strategies. Short term explains targets and strategies for 2020, 2030 and the long term is to meet the gas reduction target through economic analysis that measures how to cost effectively achieve decarbonization by 2050.

Energy strategy 2020 and 2030 (2030 energy strategy) aims to reduce greenhouse gas by 40% and contribute to renewable energy for amounts of 27% by the year of 2020 and 2030. Strategy 2050 (Energy Roadmap 2050) is achieving the 80% to 95% reduction in greenhouse gasses compared to 1990 levels by the year of 2050. Moreover, this Energy Union is implementing previous energy policies and meeting the decarbonization needs of integrated European energy market for energy security, solidarity and trust. In European energy market, energy efficiency and securing reliable energy in affordable prices is the main challenge. To get the energy policies reliable, European Union keeps three main goals; security of supply, competitiveness and sustainability for energy supply.

Security of supply is how to cope with unstable energy crisis depending on the Russia or other neighbor countries' states because of political issues. To disable unstable political and economic situations, not only focusing one country for energy trading, but diversifying supplier countries is necessary for the whole EU member countries. EU energy import dependency accounts for 54% for all fuels. (Energy Roadmap 2050) To cope with this, applying usable renewable energy as district heating is also another method to respond the security of supply. Energy competitiveness and sustainability is solutions to get the securities and stabilities as installing gas and oil pipelines and getting the safe investment source for energy requirements. Adopting higher technologies to get the better energy efficiencies is another method to pursue the energy competitiveness and sustainability. To achieve three main goals, practical methods can negotiate. Main strategy is reducing greenhouse gas, increasing higher energy efficiency and getting more energy from renewables.

Finland has good energy source with biomass in this case. By the United Nations Environment Program (UNEP), bioenergy accounts for 20 % of primary energy consumption in Finland and 10 % of electricity demand. (Sustainable Buildings and Climate initiative) By the International Energy Agency (IEA), Finland occupies the highest energy consumption per capita among other countries. As other highly industrialized countries conduct, energy efficiencies inside of industry is also main target to achieve. Smart grid or district heating system inside of local city and the whole country can belong to this target.

For other energy strategy, EU constitutes emission-trading system (ETS) to strengthen the basis of the EU energy policy to reduce the greenhouse gas cost effectively. Within Cap system, carbon emission allowances can trade as the method of receiving or buying. ETS monitors the amounts of greenhouse gases and finally carbon emission amount could shrink. ETS policy is also included into the short-term energy strategy inside of EU in the view of phase 3. Compared with phase 1 and 2, phase 3 is more wide arranged cap system not only focused on the single country itself. Auction method uses instead of free allocation of cap in phase 3. (EU ETS Handbook) In addition, 300 million allowances allocates into this step for the new entrants reserve funding (NER 300) mechanism inside of EU. Phase 3 of cap system for ETS demonstrates how energy system becomes wider and huger than previous steps. The last policy inside of EU is Energy Efficiency Directive (EED). EED establishes bunch of measures to let EU reach its 20 % energy efficiency target by 2020. The strategies inside of EED contains several measures such as 1.5 % energy savings per year by implementation from energy distributor or energy-sales retail companies. Moreover, about building field, every year, EU governments recommends to conduct energy efficiency renovation at least 3 % they possess or occupied by the floor area.

To satisfy EU energy policies and requirements, Finland demonstrates different concepts of referendums. Among those, concentrating more on building energy needs to consider in the scope of energy consumption by the United Nations Environment Program (UNEP) data. According to the UNEP, the building energy occupies the 40 % of global energy, 25% of global water, 40% of global resources and approximately 33% of greenhouse gas emissions. When it comes to the building sector of the whole industry of the world, it is estimated to be worth of 10% of global GDP (about USD 7.5 trillion) and employs 111 million people in that field. In this scope, keeping the higher energy efficiency and getting lower GHG inside of building energy system components should consider for energy saving policies in EU.

There are several methods to deal with building energy solutions. To begin with, Zero energy building or nZEB (nearly zero energy building) can negotiate. Green Building Council (GBC) in Finland concerns about sustainable development and life cycle of green building industry. ZEB or nZEB demonstrates how renewable energy uses inside of building system and when the grid energy connects with ZEB or nZEB, achieving energy from renewables can be more than electricity consumption it requires; it is energy-plus-house.

In Finland, Järvenpää (Built in 2010 by GBC Finland) is the first site to build the ZEB in 2010 and takes effect in 2020. It supplies with geothermal heat pumps and 72 solar panels. In addition, ventilation system recovers about 80% of heating for reuse. When it produces surplus energy, it sells back the excessive energy into the grid system. In this way, smart grid lets neighbor buildings connected for selling surplus energy and buying deficient energy respectively.

In the scope of energy network system, two methods generally regards. For the electricity network, smart grid system links among buildings with power station. Furthermore, for the heat network system, it considers district heating, when natural gas piping usually applies into the district heating network. In Finland, almost 80% of district heating production based on Combined Heat and Power Generation (CHP) is equipped. In the same time, one-third of electricity obtained from CHP generation operates and it is the biggest figure inside of Europe by Finnish Energy (Finnish Energy, combined heat and power generation). CHP plant usually builds up and applies in the Nordic countries for energy efficiencies. While for other EU countries, CHP plant amounts for only around 10% of the whole electricity production, Finland occupies the most in energy producing method. Because CHP employs leftover heat after electricity generation, into other heat usage through hot water system. Thus, it is more energy efficient and useful than other plant, which lets used-energy, go into the cooling tower or flue gas.

In this thesis, energy system inside of house considers to connect with district heating and grid system when energy offers from CHP plant in Finland. However, in most cases, energy system and components inside of building are zoomed in more than explaining the grid system and district-heating network connected through the energy components. For the energy components set up, higher energy efficient system components equipped with present Finnish building demonstrates with two heat pumps and solar collector before describing space heating and domestic hot water system. Sample building regards as single-family house in simulation software and this house installs inside of Helsinki Area in Finland. For the lower carbon society, energy policies and strategies in EU could consider for building model. Less energy consumption inside building model can lead to the energy saving in the whole industry.

1.2 Research objective and outline

The objective of this thesis is to study optimal design and control of thermal solar storage system with two tanks model and get the optimal size of two thermal tanks and the area of solar collector. This building model acknowledges connecting with the grid and districting heating network; heat pump components connects to the grid and district heating network communicates with the thermal solar collector on the roof of the house. Purchasing the electricity from the grid does not calculate inside of the system, less consumption of electricity from heat pump recommends for choosing the suitable size of tanks and solar collector in the view of optimization. Keeping less electricity usage and the higher efficiency of energy system is the main goal of this thesis.

Energy efficient building designs with two ground source heat pumps with two thermal tanks and one solar collector. Building model generates from the simulation software IDA

ICE (version 4.7.1). Control and the optimization completes with Matlab using the Life Cycle Cost (LCC) considering fluctuating economic parameter.

To get the optimal size of thermal tanks and solar collector, heat demand from the radiating system, which directly connected to the AHU and generally used for space heating heat demand and hot water consumption for the occupants is considered. Space heating usually works from the Air Handling Unit and hydraulic system called radiator. In Finland, heating the building during winter season is more important than cooling in summer season. Compared with Energy Efficiency Ratio (EER) with air conditioning performance system, reckoning Coefficient of performance (COP) on, especially heating COP of heat pump demonstrates for calculating electricity consumption. Energy system only considers sensible heat not regarding latent heat. Domestic hot water is consumption of water usage depending on the occupants' behavior. This building considered as single-family house, high temperature tank connects for offering domestic hot water for the whole building. Before offering hot water through high temperature tank, lower temperature tank uses for preheating and space heating.

In this way, two tanks are connected each other and separately employed for space heating and usage of domestic water consumption. Achieving thermal comfort, energy saving and energy efficiencies with the lowest price is important goal to conduct. After making the building model, heat demands gathered from the IDA ICE software and connection of two-tank model completes from the Matlab software for the control modelling. Two tank models generated from the schematic beforehand demonstrates to explain the different heat demand and functions between low temperature tank and high temperature tank. For control is dependent on the temperature for each tank model and building model, schematic of single family house with energy system components are required. Optimization shows how two objective function works for satisfying the less electricity consumption in geothermal heat pumps and high efficiency of the building model using solar collector in the system.

1.3 Structure of thesis

High-energy efficient type of building relies on the heating or cooling performance inside of system components. Improving the heating or cooling performance along with substantial energy savings could conduct by activating energy efficiency measures. Electricity consumption of the heating, ventilation and air-conditioning(HVAC) system occupies the most part, 40% of the whole building energy usage in the residential and commercial building by the US. Energy Information Administration data. Thesis employs three types of building to get the effect of insulation and selects suitable energy components for higher building efficiencies and cost of components.

Literature review accomplishes beforehand starting thesis work. In most cases literature review was checked that how predictive control with model based and data based control can be done in other articles. Those categorize with different types of predictive control method. This literature review was helpful in the view of control chapter before conducting optimization.

In this thesis, control between energy components conducts depending on temperature of two thermal tanks. When the lower temperature tank exceeds 55°C, valve between lower temperature and higher temperature tank opens and preheated water goes directly into the higher temperature tank. Control bases on the individually coded work from Matlab and building model simulates from the simulation software, IDA ICE (version 4.7.1). For the building simulation system, IDA ICE (Indoor Climate and Energy) is building energy tool for the higher occupants comfort and the lower level of energy consumption using controllers and system components. IDA ICE simulation follows regulation of ASHRAE 90.1 in the view of choosing properties of building envelop types as well as automatic HVAC selection. Certificate of Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM) also affect influences into this software. LEED and BREEAM is the certificates for assessing, rating and certifying sustainable and environmental compatible building type. With IDA ICE, satisfying the needs of building regulation and international assessment ratio, getting the heat demand and control system is possible.

When describing system components of the building, it assumes to connect with smart grid and gets electricity cost from the Nord Pool, the biggest electricity market inside of northern Europe. Actually, Fluctuating cost of electricity inside of Nord Pool is main parameter to do control for optimization; however, this thesis demonstrates the components control only not the buying and selling cost of electricity from the grid. For applying the control of components, crucial factor inside of thesis is energy balance of two tanks. Temperature is the main parameter to optimize and control works based on temperature differences between two tanks using PI (proportional and integral) control. When considering the grid system and cost of electricity, price-based control with heat demand requires, however in this thesis, normal PI control conducts the task.

Matlab software uses after getting heat demand from the IDA ICE, optimization finalizes from the Matlab with Evolutionary-Algorithm method and Pareto front shows the result satisfying two objectives, less electricity consumption and the higher efficiency. Multi objective optimization with Non Sorted Genetic algorithm (NSGAII) from Matlab studies the suitable area for two decision variables, size of tanks and solar collector. When applying the cost of components for the Life Cycle Cost (LCC) in the system, cost of components refers from well-known dataset of the HVAC research team inside of mechanical engineering department.

After the literature review, thesis considers to draw with predictive control model. For making optimization of the thermal tank size and solar collector size, predicting the temperature of the whole weather is important to decide the heat demand of the tank. To compensate the uncertainty of predictive control, weather data can be inserted using neural network or genetic algorithm method from the present temperature to get the initial input data for the predictive model. However, in this thesis, only temperature is main parameter and it considers energy balance briefly for the more accurate data output and validating the result. When optimizing the multi objective model, accurate weather input data is important than conceptual weather input, thus present weather data is employed as the form of vector to lead the correct output. For the present weather data, Helsinki-Vantaa weather is used and IDA software operates for the one-year working input data.

Building model is single-family house with first and second floors. Occupancy behaviors and lighting data refers from the minimum requirements of Finnish building with code C3, thermal insulation code for the Finnish building. Three different type of building operates for getting the heat demand result from the simulation software. Lightweight, medium weight and massive passive weight building are employed and thermal insulations used inside of building envelop are different depending on types.

For the more accurate data result, validation conducts with IDA ICE and MOBO (Multi-Objective Building Performance Optimization) software. Validation result compares with generated one tank model with IDA ICE and Matlab together. Validation result demonstrates similar trend of output and it verifies this two tanks model.

2. Energy breakdown of single family house

2.1 Background

In European building model, residential building occupies the three quarters, the most part in the whole buildings. Inside of residential building type, single-family house constitutes 64% and apartment blocks takes up the rest (By Figure 1). To make energy efficient building and considering the Finnish building codes, modelling the single family house and modifying its energy system makes out of result easily and more effective than focusing to other type of buildings. European energy initiatives about building also targeted at the type of single-family house case and it is same to the Finnish building. (Data by the Building Performance Institute Europe – BPIE, March 2014)

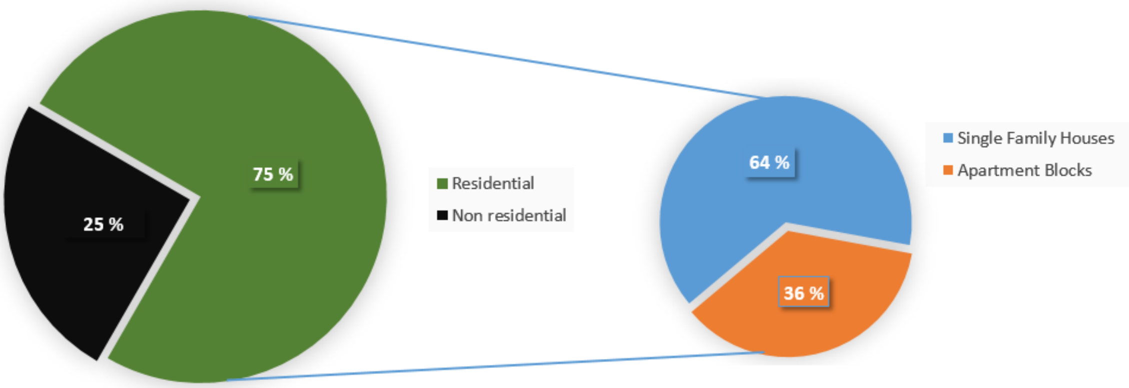


Figure 1. European buildings divided into residential and non-residential sectors

Finnish houses are more restricted about the density of population compared with other European houses even though its high quality of living conditions. Amounts of dwelling (2.9million) exceeds the number of households (2.6million) and the common size of average household is 2.05 person. Another pattern is one or two consisting households manage 75% of Finnish dwellings. (By the Hannonen et al.) For this pattern, optimizing the building components of single-family house is more required than any other building type. In this thesis, following the trend of building types in European countries and Finland, it employs single-family house as the model of the house. Especially it choses Finnish current building with two-story house for modelling and optimization.

Inside of energy consumption annually of the single-family house, heat demand from space heating occupies the most part, almost the half. In addition, hot water consumption occupies the second the fifth of whole consumption. Two storage tank inside of the system demonstrates the two main consumption of energy inside of the house and other usages of lights, equipment and occupants' usage back up the rest. As pie chart of Figure 2 shows from the Vantaan Energia company energy consumption from hot water consumption and space heating for radiation is main parameter to optimize for energy efficiency of the whole house. In this thesis, to make better energy controlled type of building, two thermal tanks separate to use space heating and domestic hot water respectively.

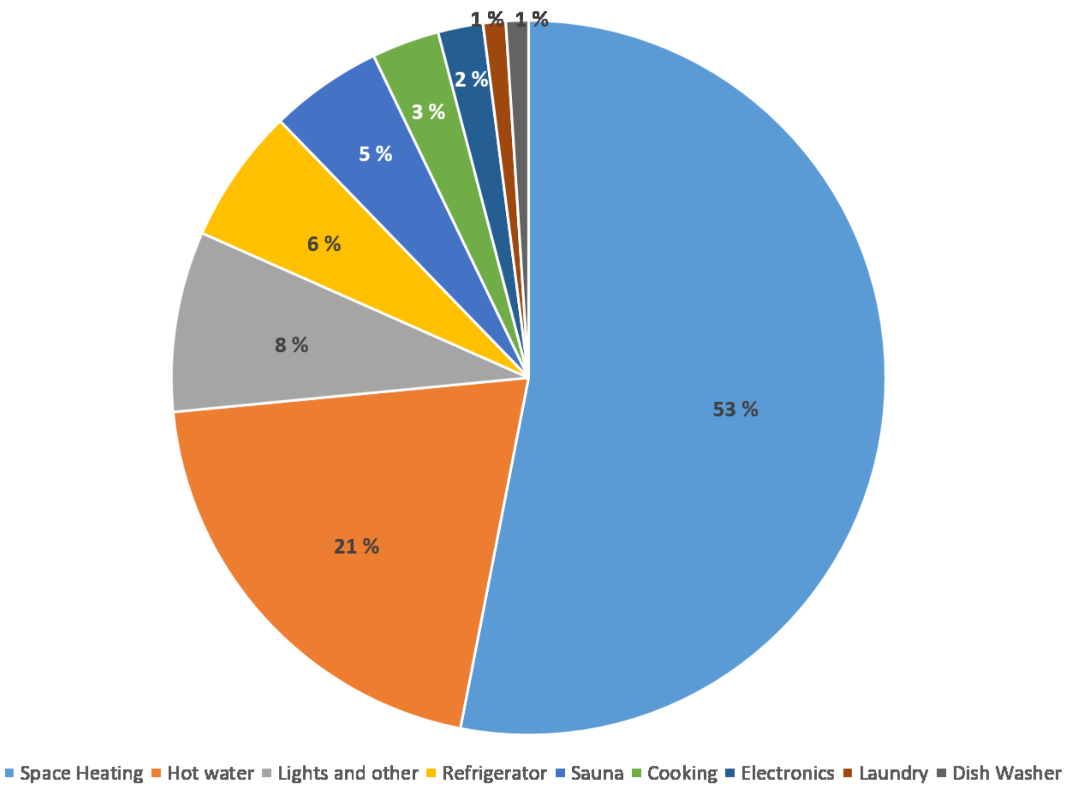


Figure 2. Annual energy consumption (example: 4-person home, 120 sqm, electrical heating Total 18300 kWh)

By the pie chart of this result, domestic hot water and space heating occupies in the most case for annual energy consumption of the house. Space heating is heating method in the limited room with radiator or employing floor-heating method. Domestic hot water is water consumption method from the cold water supply to the hot water offering for the kitchen or bathroom. It can also use as radiating system or boiler, pipeline between the hot and cold waters are different.

Building research establishment in Scottish government releases data about energy consumption in different Northern European countries as Denmark, Finland, Norway, Scotland and Sweden. Article shows how energy consumption is demonstrated when it comes to various energy component usage in each country using their calculation method. As figure 3 indicates, space heating occupies the most in all countries. The case of Finnish building is not different to general case of northern European countries. Northern European countries employ the hot water tank connected with district heating pipe for warming up and using the radiator for space heating while many buildings located in Asian countries adopt residential air conditioning system in their own house as residential method. (By the data of The Japan Refrigeration and Air Conditioning Industry Association in April 2016)

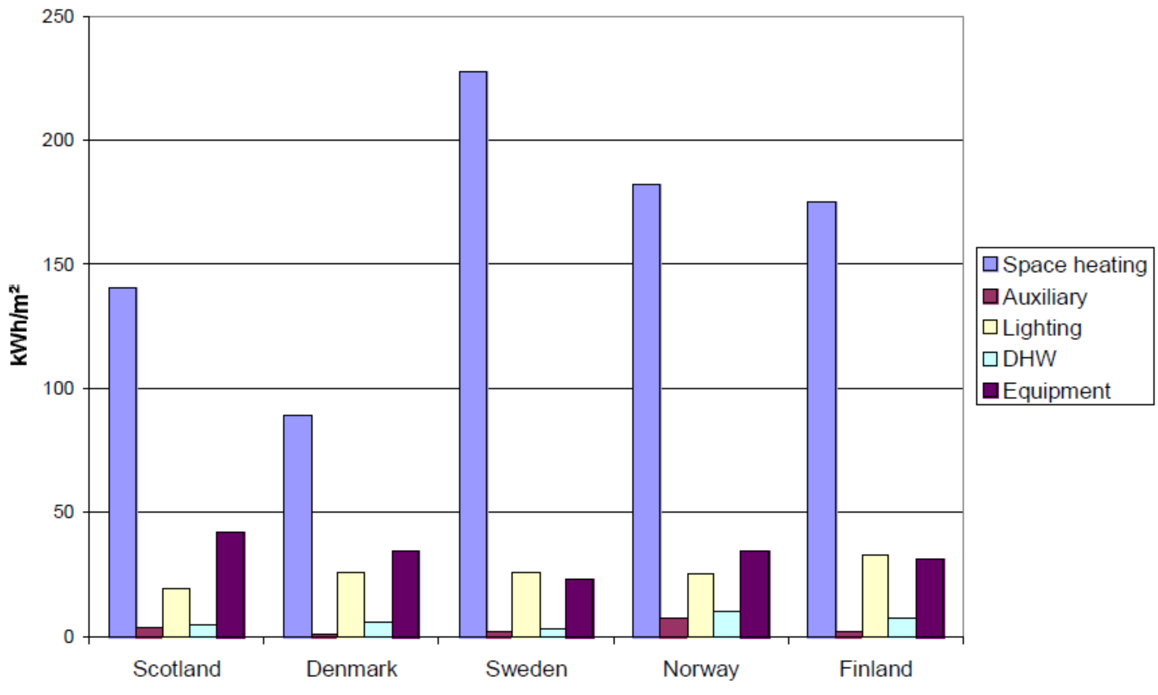


Figure 3. Energy required (kWh/m²) for space heating, auxiliary, lighting, DHW and equipment of benchmark building by calculation method of each country

In the thesis, single-family house decides for satisfying the requirements of Finnish building type for residential usage. In addition, heat demand from space heating and domestic hot water is dealing with the high priority to contribute to the energy breakdown of single-family house.

Influence of energy efficiency from the background of Kyoto protocol, Finnish energy and climate strategy aims to reduce the greenhouse gas emission. Technical regulations and instructions from the Ministry of the Environment degree arranged seven different sections from Finnish building code. In the view of energy efficiency of building, D3 regulation decides clause from 2012 for building regulations and guidelines while D5 is the calculation of energy consumption and heat loss of the building and the last C4 code generates for the thermal insulation instructions. As this regulation defines, D section is applied by the data from 'HEPAC (Heating, Plumbing and Air Conditioning)'and energy management. E indicator (so called E-value) is key driver to permit the energy consumption of the building and D5 stipulates with grid system. D3 is general guideline for the Finnish building and decides the ventilation efficiency and supply air rate to the building when different type of building applies. Temperature to keep constant for ventilation decides by the building guideline in the D section. Efficiency of building envelope is different by the insulation material to use, C4 states in the Ympäristöministeriö, 2012, the Finnish building code.

2.1.1 Single Family house model in the Finnish Building Types

Finnish building code D3 specifies the energy efficient operating regulation in case of different building categories. By the size and usage of building, nine different types categorize to regulate the supply air rate from outside, heating limit and cooling limit. Different types of building decides different set points in temperature and supply air rate. In this thesis, single-family house is selected and by the data result of table 1. Building categories with setting points used in energy demand calculations (Ympäristöministeriö, 2012); its heating limit temperature is constraint as 21-Celsius degrees. Floor area of model is 180m^2 and volume is 468.1m^3, in the shape of two-story house building schematic model.

Class	Building type	Supply air rate from outside (dm3/sm2)	Heating limit (C°)	Cooling limit (C°)
Class 1	Individual one-family houses and row houses	0.4	21	27
Class 2	Residential apartment buildings	0.5	21	27
Class 3	Office buildings	2	21	25
Class 4	Shop/store buildings	2	18	25
Class 5	Accommodation buildings	2	21	25
Class 6	Teaching buildings and kindergartens	3	21	25
Class 7	Sport buildings excluding swimming halls and ice stadiums	2	18	25
Class 8	Hospitals	4	22	25
Class 9	Other buildings	-	-	-

Table 1. Building categories with setting points used in energy demand calculations (Ympäristöministeriö, 2012)

When applying building model for getting the heat demand, indoor temperature considers keeping as 21 Celsius degrees. Building in Finland with ground source heat pumps need heating radiating system more than cooling system, thus building temperature considers keeping as 21 degree and heating energy demand estimates for generating energy demand of the building.

For the building envelope, this model of the house more focuses on the Finnish weather. Finnish building is usually well isolated with insulations. Long term harsh winter season affects enormous impact on Finnish building wall thickness and material in the building type of Finland. (Subba et all 2015). To cope with harsh Finnish winter case, different type of building envelope decides by the material and wall thickness following the Finnish building code C4. Light weight, middle weight and massive passive weight of buildings are decided and most of them have different insulations inside (Table 2) from the comparison of 1960 Finnish building type with standard 2010 type in Alimohammadi et al. 2014.

In the type of lightweight, materials are wood frame construction. Medium weight building type is similar to the lightweight except of roof construction; concrete materials employs into this structure. In addition, the massive weight building type, most of them are concrete and equipped well for the long winter season in Finland. In this thesis, light weight, medium and massive thermal mass buildings are used from the SAGA (Smart Control Architecture for Smart grids 2012-2016) project, 2010 standard type for the modelling and optimization in the type of single family house.

Type of building structures	**Elements of construction**	**Material composition (thickness of the layer) /external structures from inside to outside**	**Overall thickness(mm)**
Light	External wall	Gypsum (13 mm), wooden frame + mineral wool (540 mm), wind shield board (9 mm)	562
	Internal wall	Gypsum (13 mm), wooden frame (40 mm), gypsum (13 mm)	66
	Roof	Gypsum (13 mm), wooden frame + mineral wool (150 mm), mineral wool (375 mm), water proof sheet (10 mm)	548
	Base floor	Wood (14 mm), wooden frame + mineral wool (436 mm), wind shield board (9 mm)	459
	Intermediate floor	Wood (15 mm), particle board (22 mm), wooden frame (150 mm), gypsum(13 mm)	200
Medium	External wall	Gypsum (13 mm), wooden frame + mineral wool (540 mm), wind shield board (9 mm)	562
	Internal wall	Gypsum (13 mm), wooden frame (40 mm), gypsum (13 mm)	66
	Roof	Gypsum (13 mm), wooden frame + mineral wool (150 mm), mineral wool (375 mm), water proof sheet (10 mm)	548
	Base floor	Wood (14 mm), light weight concrete (15 mm), concrete (100 mm), EPS thermal insulation (480 mm)	459
	Intermediate floor	Wood (15 mm), particle board (22 mm), wooden frame (150 mm), gypsum(13 mm)	200
Massive	External wall	Light weight concrete block (130 mm), polyurethane (340 mm), light weight concrete block (90 mm)	560
	Internal wall	Light weight concrete block (100 mm)	100
	Roof	Filler (5 mm), concrete (100 mm), mineral wool (490 mm), water proof sheet (10 mm)	605
	Base floor	Wood (14 mm), light weight concrete (15 mm), concrete (100 mm), EPS thermal insulation (480 mm)	609
	Intermediate floor	Wood (15 mm), light weight concrete (15 mm), concrete (100 mm), filler (5 mm)	135

Table 2. Properties of different type of buildings in Standard 2010
For simulation from the SAGA project Aalto University (Alimohammadi et al. 2014)

In the single-family house modelling, two thermal tanks study for domestic hot water and space heating. It employs low temperature tank for radiating the building envelope inside the house and high temperature tank for tenants' hot water consumption. Low temperature tank requires more energy demand than domestic hot water tank for preheating the tank and warming up the building envelope. To compensate energy needs for low temperature tank, solar thermal installed on the roof of the house connects to the low temperature tank operating the system. The sum of energy need from the building envelope and inner room is same as the heat demand supplied from the Air Handling Unit on the ceiling of the indoor building for radiating the whole system.

2.1.2 Description of case study for two tanks with solar collector model

Energy system inside of building model in the thesis is composed of two geothermal heat pumps with thermal tanks and solar collector. From the modelling of the system, it employs low temperature thermal tank for radiating the building inside and high temperature thermal tank for hot water consumption. To make energy system more efficient, appropriate heating, ventilation and air conditioning (HVAC) is the key factor to keep the comfortable, healthy living and working environment inside of house. Electricity consumption inside of the HVAC system occupies the 40% of the whole building electricity consumption by the U.S.Green building Council (USGBC). Improving the cooling and heating performance of the building with energy saving can be achieved by implementing energy efficiency methods. Most suitable method is focusing on the high-energy efficient HVAC system and choosing the suitable size of components for the cost reduction and energy efficiency. In this thesis, it chooses optimized size of tanks and solar collector to make current building as the better-adjusted energy system.

In the building simulation software IDA ICE, it only generates one tank model with solar collector. For higher energy-efficient building, two-tank model operating separately in the use of domestic hot water and space heating is required. Schematic of building model demonstrates how two tanks operate individually for the usage of domestic hot water consumption and radiating. To control two tanks, temperature is main parameter and heat balance should calculate before conducting the control and optimization. Self-coded Matlab software shall finalize the control and optimization.

In the view of the satisfaction for the heat demand of different types of building, air handling unit system connected to the low temperature tank and building together supplies the whole energy into the building from the tank model. Inside of building model, temperature difference and heat transfer discusses before getting heat demand. Building model assumes to connect with air handling unit directly, outdoor air temperature contacts to the wall of the building and air-handling unit directly. It shows below schematics as figure 4. Figure 4 demonstrates how indoor air temperature and temperature of structure decides by outdoor temperature and heat capacity factors.

To make room keeping temperature as 21˚C, heat supply from air handling unit is regarded as same as gained heat from the whole building in the way of energy balance. Inside of the building, gained thermal loads divide as two parts. One is convection thermal loads and the other is radiation thermal loads in the view of space heating. Whole energy transfer inside of room derives from the low temperature tank and it transfers energy into the Air Handling unit and building.

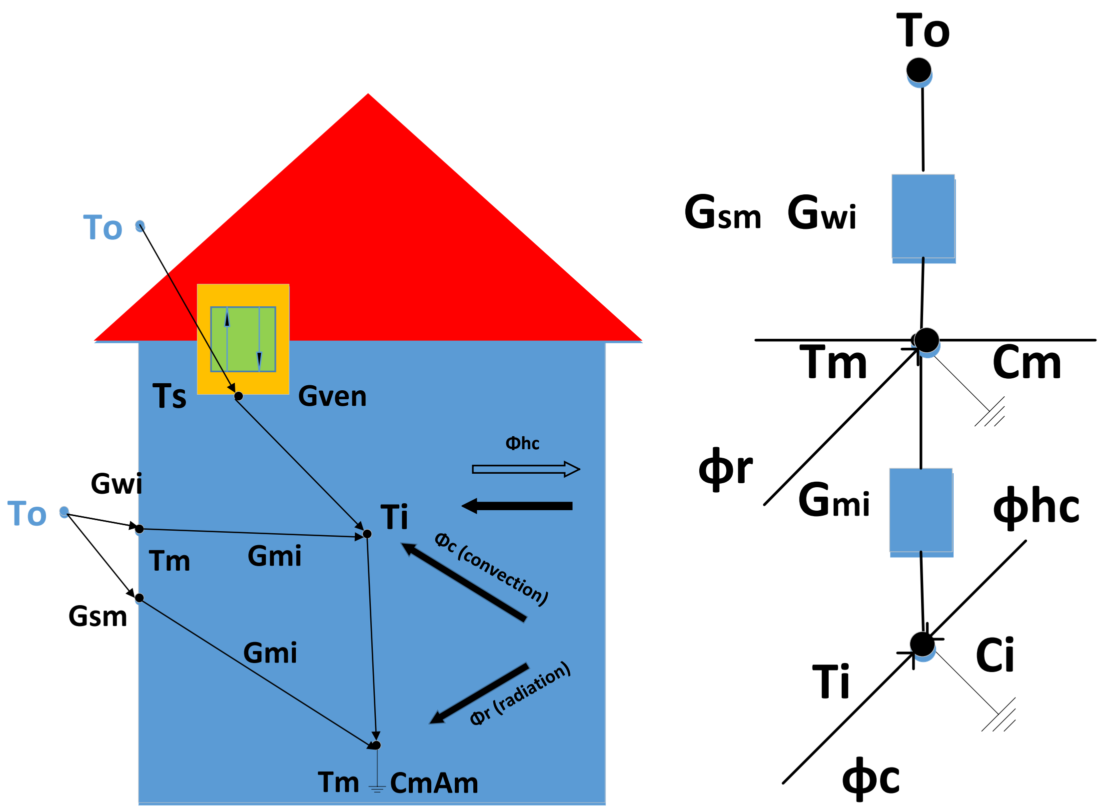


Figure 4. Equivalent electro circuit representing the heat transfer in the specified building boundary system

The whole heat demand of the building is same as the heat transfer from the low temperature tank to the Air Handling unit. When energy transfer occurs from the low temperature tank to the Air Handling unit, energy passes through material of the wall, shell of window and air between wall and indoor air. How heat transfer occurs through the wall and window shows in the schematic of figure 4. Left picture demonstrates direction of heat transfer from the outside to the inside of the building with the method of conduction, convection and radiation. Right picture shows detail heat transfer by electro circuit in the restricted building boundary of single-family house in the way of conduction.

Heat gain from the zone (equation 1) is summation heat between wall insulation and air, wall materials and air conduction inside of the room.

$$\dot{Q}_{\text{zone}} = \dot{Q}_{\text{AHU}} = \dot{Q}_{\text{materials + air}} + \dot{Q}_{\text{materials}} + \dot{Q}_{\text{domestic}} + \dot{Q}_{\text{window}} + \dot{Q}_{\text{convection}} + \dot{Q}_{\text{radiation}} \quad (1)$$

where

$\dot{Q}_{\text{zone}}$	Heat Power in the building
$\dot{Q}_{\text{AHU}}$	Heat Power in the AHU
$\dot{Q}_{\text{materials + air}}$	Heat Power between materials and air
$\dot{Q}_{\text{materials}}$	Heat transfer in the material of the wall
$\dot{Q}_{\text{domestic}}$	Heat Power inside of building
$\dot{Q}_{\text{window}}$	Heat Power from window
$\dot{Q}_{\text{convection}}$	Heat Power from convection
$\dot{Q}_{\text{radiation}}$	Heat Power from radiation

Heat gain from convection (equation 2) is the total sum of the gained heat from equipment, occupants' behavior and machine.

$$\dot{Q}_{\text{convection}} = \dot{Q}_{\text{equipment}} + \dot{Q}_{\text{people}} + \dot{Q}_{\text{machine}} \quad (2)$$

where

$\dot{Q}_{\text{convection}}$	Convection heat load (φ_c)
$\dot{Q}_{\text{equipment}}$	Internal heat gain from equipment
$\dot{Q}_{\text{people}}$	Internal heat gain from people
$\dot{Q}_{\text{machine}}$	Internal heat gain from machine

Radiating heat gain (equation 3) is energy demand from the space heating and this one connects with the low temperature tank of the above energy system mentioned before. Radiation energy describes to get from equation 3. Area of radiator and temperature between panel and surface decides for the heat demand of radiation by the Tähti et al.

$$\dot{Q}_{\text{radiation}} = \Sigma\, h_{\text{radiation}} * A_{\text{panel}} * (T_{\text{panel air}} - T_{\text{surface}}) \quad (3)$$

where

$\dot{Q}_{radiation}$	Heat power from radiation (φ_r)
$h_{radiation}$	Heat Transfer coefficient ($Wm^{-2}K^{-1}$)
A_{panel}	Surface Area of panel
$T_{panel\ air}$	Air temperature faced to the surface of the panel
$T_{surface}$	Surface temperature of the panel

Temperature of inside of the building calculates considering the material temperature between the building walls. Equation (4) shows how material temperature is decided by the radiation heat load and the heat gain from the outside temperature, material temperature and indoor temperature.

$$C_m \frac{dTm}{di} = G_{sm}(T_o - T_m) + G_{mi}(T_i - T_m) + \varphi_r \quad (4)$$

where

C_m	Heat capacity of building structure
G_{sm}	Material thermal conductance
G_{mi}	Thermal conductance between materials and indoor air
T_o	Temperature of outdoor node
T_m	Temperature of material node
φ_r	Radiation heat load

Equation (5) demonstrates the amounts of space heating heat load is required in the view of balance equation for the indoor heat gain.

$$C_i \frac{dTi}{dt} = G_{ven}(T_s - T_i) + G_{wi}(T_o - T_i) + G_{mi}(T_m - T_i) + \varphi_c + \boldsymbol{\varphi_{hc}} \quad (5)$$

where

C_i	Heat capacity of indoor air

G_{ven}	Thermal capacity of ventilation (AHU)
G_{win}	Thermal conductance of window
G_{mi}	Thermal conductance between materials and indoor air
T_s	Temperature of ventilation (AHU) supply air node
T_m	Temperature of material node
T_i	Temperature of indoor air
φ_c	Convection heat load
φ_{hc}	Space heating heat load

Indoor temperature of the house should keep as 21˚C. It decides indoor temperature for 24 hours without space heating heat load, by the initial temperature in the way of Euler implicit method and indoor temperature fluctuates by the conductance of window, AHU, conductance between material and air and the convection heat load. To make indoor temperature constant, space heating with ventilation system is required. Formulae (6) demonstrates how indoor temperature keeps constant while every time step tries with Euler Implicit method. Time step is 1 hour and new approximation (unknown variable) is dependent on the previous indoor temperature node. By iterating initial temperature value, it generates 8760 samples in the end. It is one-year data when IDA simulation adopts.

$$T_i^n = \frac{\frac{Ci}{\Delta t}T_i^{n-1} + G_{ven}{*}T_s + G_{wi}{*}T_o + G_{mi}{*}T_m + \varphi_c + \boldsymbol{\varphi_{hc}}}{\frac{Ci}{\Delta t} + Gven + Gwi + Gmi} \tag{6}$$

where

n number of iteration

Temperature of material node shows with thermal conductance of material node, conductance between material and air, radiation heat load and previous temperature of material node with Euler implicit method. (Equation 7)

$$T_m^n = \frac{\frac{Cm}{\Delta t}T_m^{n-1} + G_{sm}{*}T_o + G_{mi}{*}T_{i-1} + \varphi_r}{\frac{Cm}{\Delta t} + Gsm + Gmi} \tag{7}$$

Euler method presents, when equation (6) and (7) combines, space heating heat load decides by this sum up.

$$\varphi_{hc} = (Gven + Gwi + Gmi){*}Ti - Gwi{*}To - Gven{*}Ts - Gmi{*}Tm - \varphi_c \tag{8}$$

Space heating is dependent on the indoor temperature, outdoor temperature and convection heat load. As discussed previous, convection heat load is the gross sum of gained inner heat from equipment, machine and tenants' behaviors of the building model. To calculate heat load from the simulation software, it is necessary to draw house model and make a separate zone by different rooms and spaces inside. Figure 5 demonstrates how different materials applies into the walls by visualization. Floor area of 180m^2, volume of 468.1 m^3 model adopts to this single-family house.

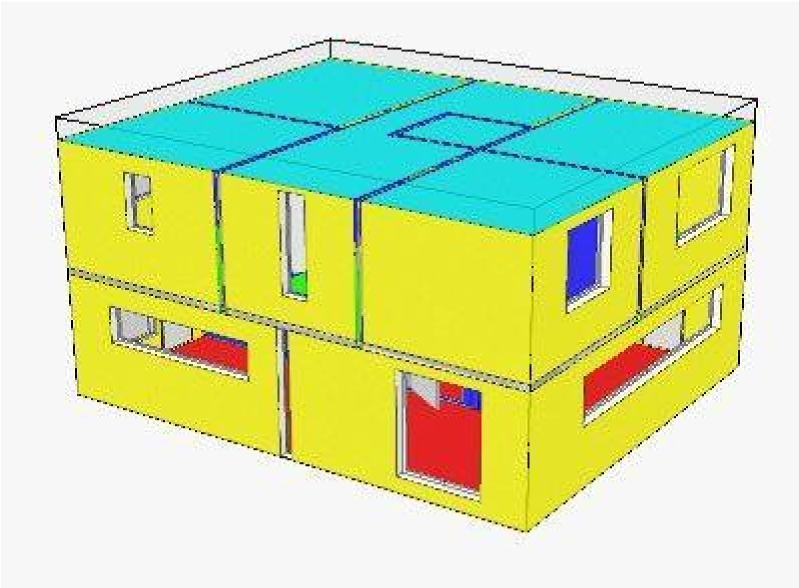


Figure 5. Visualization of two story building in the form of single-family when passive massive material adopts.

Lightweight, medium weigh and passive massive weight of materials applies into the wall of the building for insulation. In this figure, passive massive materials are studied thus concrete are used for thick wall structure. To make inner temperature of building keep constant, minimum usage of electricity in heat pump for space heating is required for the efficient method of energy system. Energy efficiency system with two heat pumps and two thermal tanks with solar collector can design inside of simulation software. Single-family house CAD file is imported as IFC (Industrial Foundation Classes) format into the IDA software for exact zoning the building and getting the heat demand data from each space. Inside of the whole building, spaces merge and zone as three different places for accurate calculation.

After operating building model, heat demand from the space-heating tank and domestic hot water tank works separately and connected through the Matlab code. Space heating heat demand is dependent on the equation (8) by the temperature of time step from the Euler Method. Domestic hot water is following the profile schedule of the occupants inside. When applying this work, energy balance uses for exact calculation. Inside of IDA ICE software, usually one thermal tank with one heat pump generates with solar collector system. For operating two heat pumps with two thermal tanks, operating three samples simultaneously as parallel method and combining them is required to get the result data. When initial data is decided, using default platform called Early Stage Building Optimization (ESBO) Plant; energy system is set and operated with components.

2.2 ESBO plant set up and simulation

IDA ICE is building simulation software for indoor climate and energy. It is specified version of General IDA software and contains more indoor individual zone control for the complete building envelope. When IDA ICE simulation software employs, it receives initial input data from users. Users can choose or make their own weather vector by outdoor temperature, humidity, wind speed and radiation and temperature from solar energy. From version 4.5, IDA ICE shows new wizard interface called ESBO (early stage building optimization) and updated room wizard. Installed wizard, ESBO plant mainly uses for generating the building model with energy components.

ESBO plant is building-optimization simulation program with different geometry of building drawing. Various insulation and envelopes adopts to the building connecting solar thermal and tank system. External and internal walls, roof and floor materials are object to passive massive, medium and lightweight building envelope. Selecting materials for insulation of building, connecting central system with ESBO plant is required. ESBO plant materializes the drawing and type of building importing CAD objects and images. Building information models (BIM), CAD and vector graphic files can execute for operating IDA ICE building model. BIM contains properties of the house and 3D geometries as zoning rooms, window and building body. It automatically generates the data objects from mapping the IFC dialog. Two story building in single-family house type creates from the SAGA project by the Alimohammadi et al. 2016. As figure 6 demonstrates below. After adopting the template building drawing from IFC mapping, merging the zone is necessary to install two-story single-family house for 3D model.

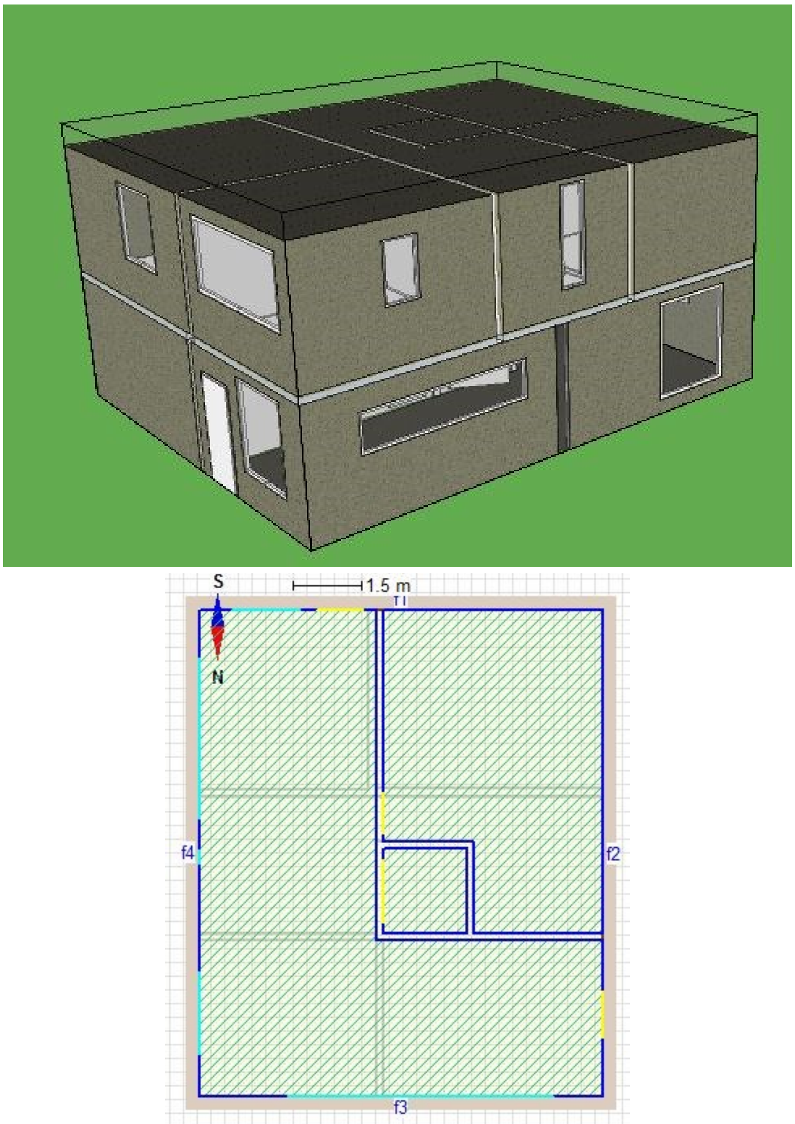


Figure 6. IFC imported file of single-family house of 2nd story building type

After that by the ESBO plant, components choose in the plant set up and used inside of the building energy system. However, this is one tank model with solar collector thus, installing two different type of building, one for the domestic hot water and the other for the radiating is demanding. Getting the heat demand and combining two tanks with one tank model comes into action with Matlab software. Row vector from the utilized energy puts to use to finalize the tank model and this conducts by the individually defined codes in the Matlab software.

Generally, solar thermal and photovoltaic connects to the single-family house with hot storage tank and heat pump component. In this thesis, ground source heat pump applies to combine with the tank. Coefficient of Performance (COP) of the heat pump is four, but it can be different in condensing temperature and evaporating temperature. (By Yrjölä et al.) Indoor climate condition regulates as basic setting for making the room temperature and air quality constant (Figure 7). Keeping indoor temperature constant is main initial input for the heat balance and in the view of getting the energy transfer from the tank and solar collector to the room of the single-family house.

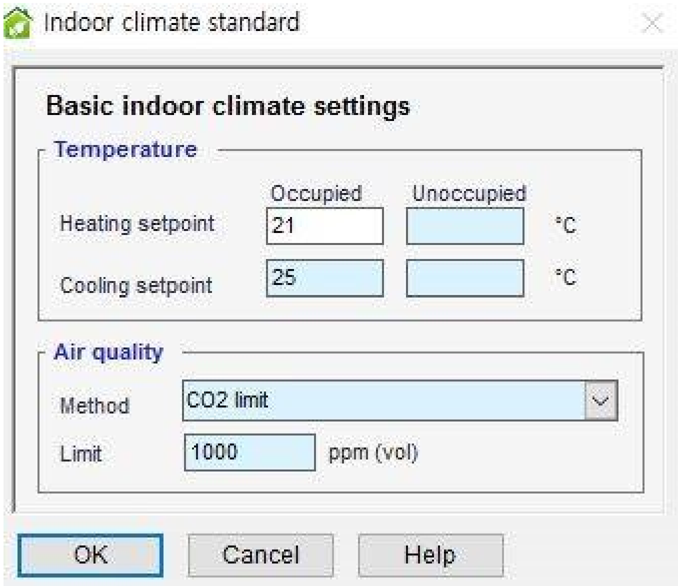


Figure 7. Indoor room condition with temperature and CO2 for thermal comfort

Internal heat gain profile depends on the heat from equipment, light and occupants. Profile schedule displays internal behavior with weekly data as figure 8 shows. Internal heat gain is composed of heat from equipment, occupants and light. Heat power from convection influences by the internal heat gains as discussed earlier with the formulae (2) mentioned before.

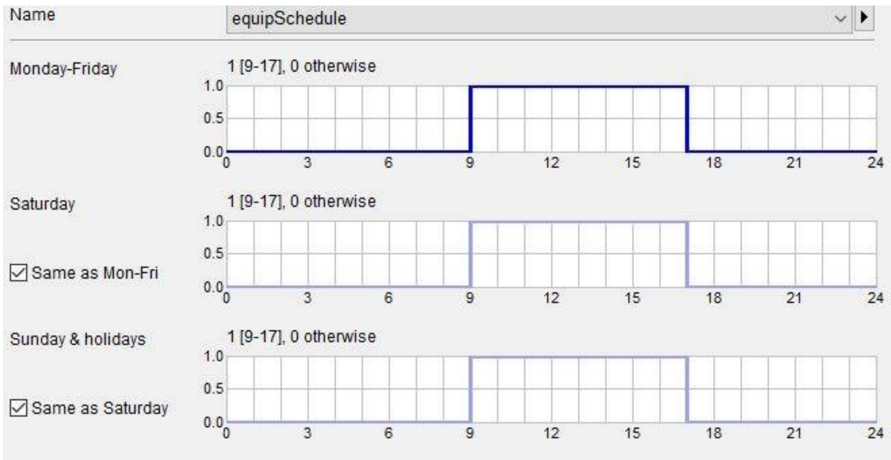


Figure 8. Schedule of Equipment, occupants and light from the internal heat gain profile

Selecting energy components and simulating with ESBO plant is required for getting the heat demand of the system. In ESBO plant, one tank model generally introduces connecting with space heating and domestic hot water consumption usage as Figure 9 demonstrates.

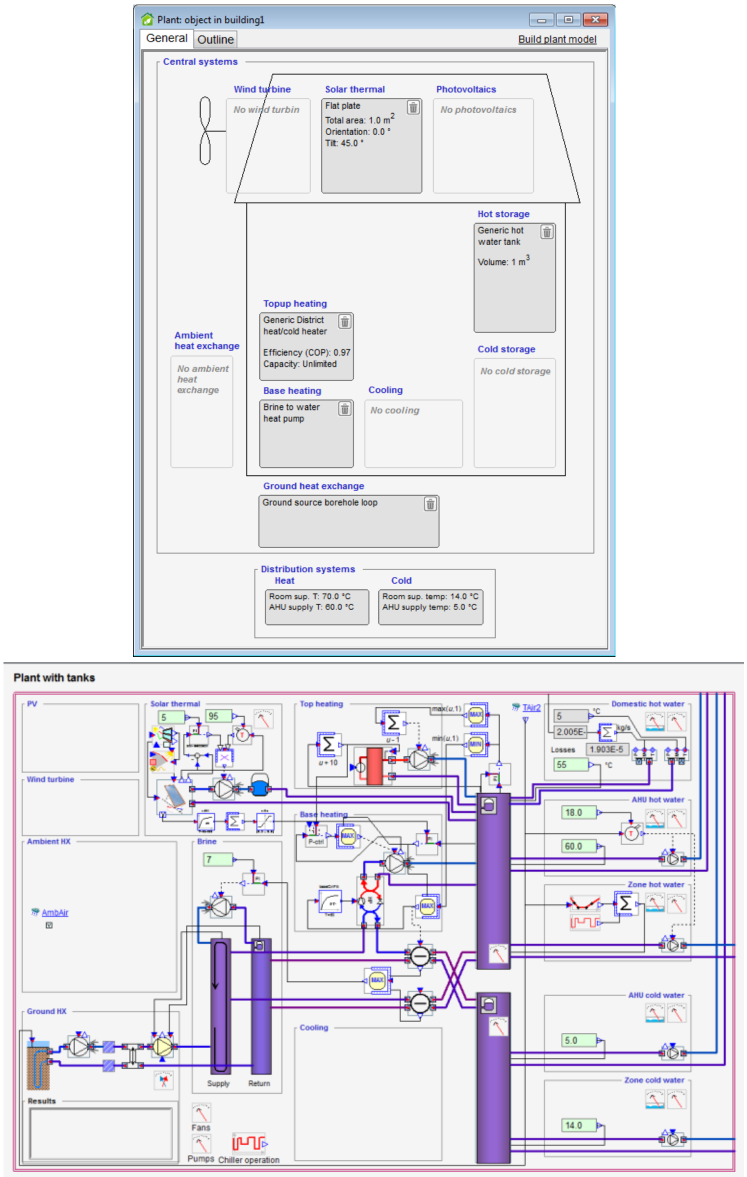


Figure 9. ESBO plant for the domestic hot water and space heating connection with one tank and solar collector

In this thesis, smart grid system considers connecting for buying and selling the electricity usage of the building, however photovoltaic is not applied. Instead, solar thermal is considered to be connected to the district heating and adopted for the compensating the heat pump operation when solar radiation and energy works. Solar thermal area changes from 1m^2 to 10m^2 for the optimization, while its installation angel keeps as 45 ° fixed and its orientation defines as 0 ° as Figure 10 demonstrates.

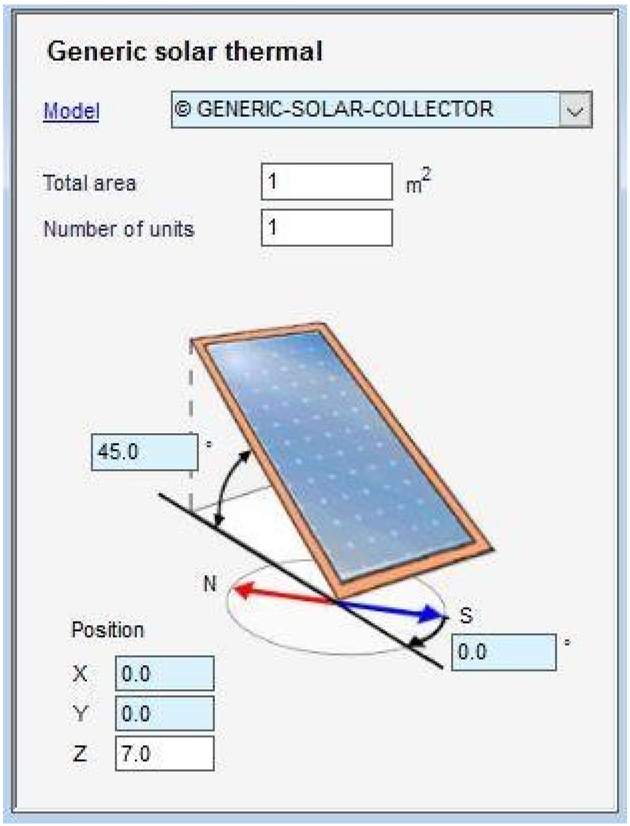


Figure 10. Schematic of solar thermal in ESBO plant

Hot storage assumes to be the tank component in the shape of cylinder for linking pipe of the water consumption usage and radiation. Hot storage has eight layers and stratified tank system applies for the exact temperature calculation. Layer of the tank varies from one to the 50, in this thesis, eight layers assumes and temperature variation happens in different layers. Insulation U value for the tank is 0.3W/m^2 °C and shape factor (height/diameter) of the cylindrical tank is five. This is initial input value for the energy computation.

In the heat pump components, brine to water heat pump applies as ground source heat pump and its type is reciprocating type with COP of the four like Figure 11 shows. Minimum evaporator temperature and condensing temperature is set as -50°C and 70°C respectively while brine evaporator temperature and hot water condensing temperature regulates as each 8°C individually. Water type brine uses in the heat pump and the auxiliary heater is equipped with the tank for running the boiler with pump system.

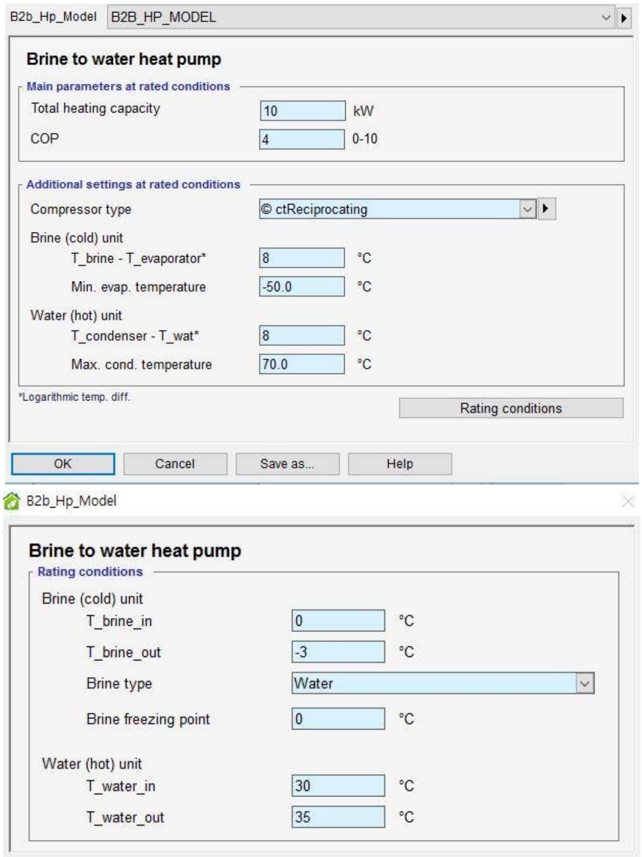


Figure 11. Schedule of Heat pump linked to the hot storage

Building model considers as two-story house with three zones. Heat demand for one-year data is get from the IDA ICE software taking account of time step as 1 hour. It decides Initial temperature as input data and next temperature after time step is depending on the previous temperature using Euler implicit method as discussed previous chapter.

For designing the building model, satisfying the occupancy behavior for thermal comfort is important. In this way, estimating clothing insulation (CLO) value or considering occupants' behaviors calculate for the stable index of predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) by the time. This thesis outlines how to make energy efficient building with energy system and satisfy the tenants of the building getting the stable PMV index for tenants. Heat Demand calculates based on temperature and energy balance of the tank. From the point of view in Predicted mean voted (PMV), indoor temperature maintains constant temperature and humidity for the thermal comfort of the room. To improve the building efficiency and thermal comfort, PMV computes as equation (9) provided by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard.

$$PMV = (0.303\exp{-0.0336M} + 0.028) \times \{ (M - W) - 3.5 \times 10^{-3} [5733 - 6.99 (M - W) - Pa] - 0.42(M - 58.5) - 1.7 \times 10^{-5} \times M (5867 - Pa) - 0.0014M (34 - ta) - 3.96 \times 10^{-8} fcl [(tcl + 273)^4 - (tr + 273)^4] - fcl \times hc (tcl - ta) \} \quad (9)$$

where

M	Metabolism rate
W	External Work
Pa	Partial water vapor pressure
ta	Air temperature
fcl	Thermal resistance of clothing
tcl	Surface temperature of clothing
hc	Convective heat transfer coefficient
tr	Radiant temperature
ta	Air temperature

The recommended acceptable PMV range for thermal comfort from ASHRAE 55 is between -0.5 and +0.5 for an interior space. From the view point of PMV, air temperature, radiant temperature, relative humidity and air velocity stays inside of comfort bounds and control system contributes to the scope of the comfort level.

In the IDA ICE, PI (Proportional Integral) controller adopts to respond temperature control of the simulation. Control system works based on the temperature sensor and PI controller system connected to the tanks and solar collector. Sensor and controller holds up the temperature signal to be in accepted range for the thermal comfort of the building envelope. PI controller is control loop feedback mechanism generally used in building control and optimization. Error value calculates measuring the difference from the set point of the temperature and processed variables, then calibrates it with proportional and integral method. Formulae (10) demonstrates manipulated variables from the sum up of proportional and integral terms. (11) is the transfer function in the Laplace domain of PI control.

$$u(t) = Kpe(t) + Ki\int_0^t e(\tau) \tag{10}$$

$$L(s) = Kp+Ki/s \tag{11}$$

where

Kp	Proportional gain, tuning parameter
Ki	Integral gain, tuning parameter
e(t)	Error (set point – process variables)
t	time

τ Variable of integration

s Complex frequency

Inside of IDA ICE, temperature set completes by the set point as figure 12 shows. Minimum and maximum temperature is set and in the heating mode, Proportional control works with radiator and in the cooling mode, PI controller runs in the actual device for the steady state of temperature in the fluctuation situation.

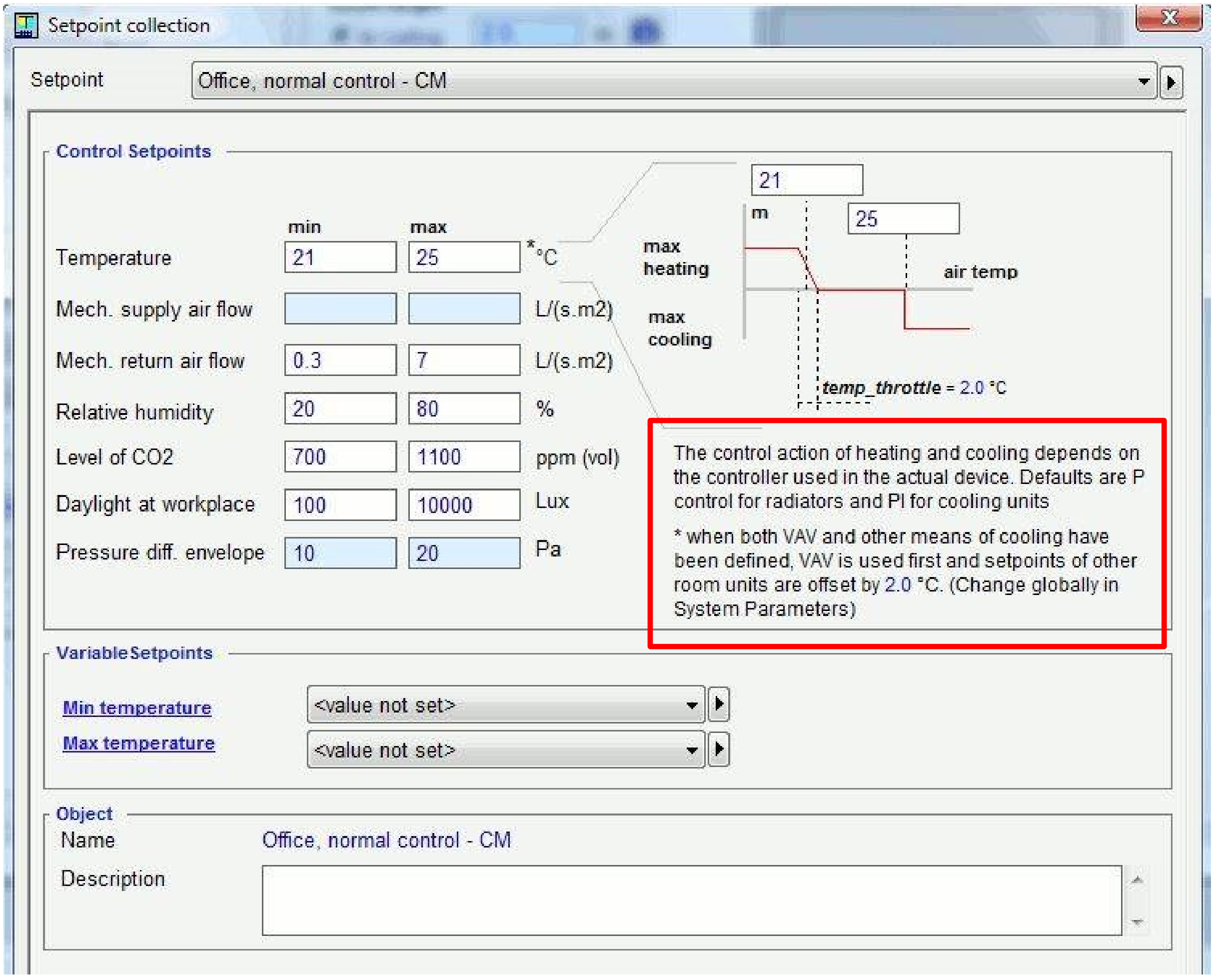


Figure 12. Set point collections with PI control method inside of IDA ICE

In the hot tank storage, temperature for radiation and space heating is determined approximately 45°C and temperature for domestic hot water consumption is set as 60°C. When it comes to the IDA ICE hot storage tank, its temperature variation inside of stratified tank has eight layers with different temperature range.

In this thesis, two thermal tank model with two ground source heat pumps are discussed different from general IDA ICE tank system. Typical system for IDA ICE is one tank model linked to one heat pump with solar collector or PV system. To satisfy the need of two storage tanks, one tank manages the space heating inside of building envelope and the other runs the domestic hot water consumption heat demand of the house. Thesis determines how to connect two tanks with Matlab coded simulation and shall check the result with multi-objective optimization method.

Lower temperature tank with solar collector operates in the beginning. Moreover, lower temperature tank without solar collector operates in the next step. Both cases contain only space heating case not considering hot water consumption. In this case, only building radiation finalizes with space heating method however, hot water consumption is zero. In addition, the last, higher temperature tank is operating with domestic hot water consumption not thinking about radiating the building work. After these three samples are operating with parallel method, optimization also to be considered depending on area of solar collector and size of tanks. Size of hot storage tank is changing from 0.5 m^3 to 2 m^3 with step of 0.5 m^3 during the size of solar collector goes from 1 m^2 to 10 m^2 with step as 1m^2. Lower temperature tank without solar collector and higher temperature tank only for the domestic hot water model generates four samples respectively and lower temperature tank with solar collector model has 40 samples. Thus, after conducting parallel method 48 samples generate the result. When building type is three different type; lightweight, medium weight and massive weight, 144 samples are finally get from the simulating the building model from the IDA ICE software.

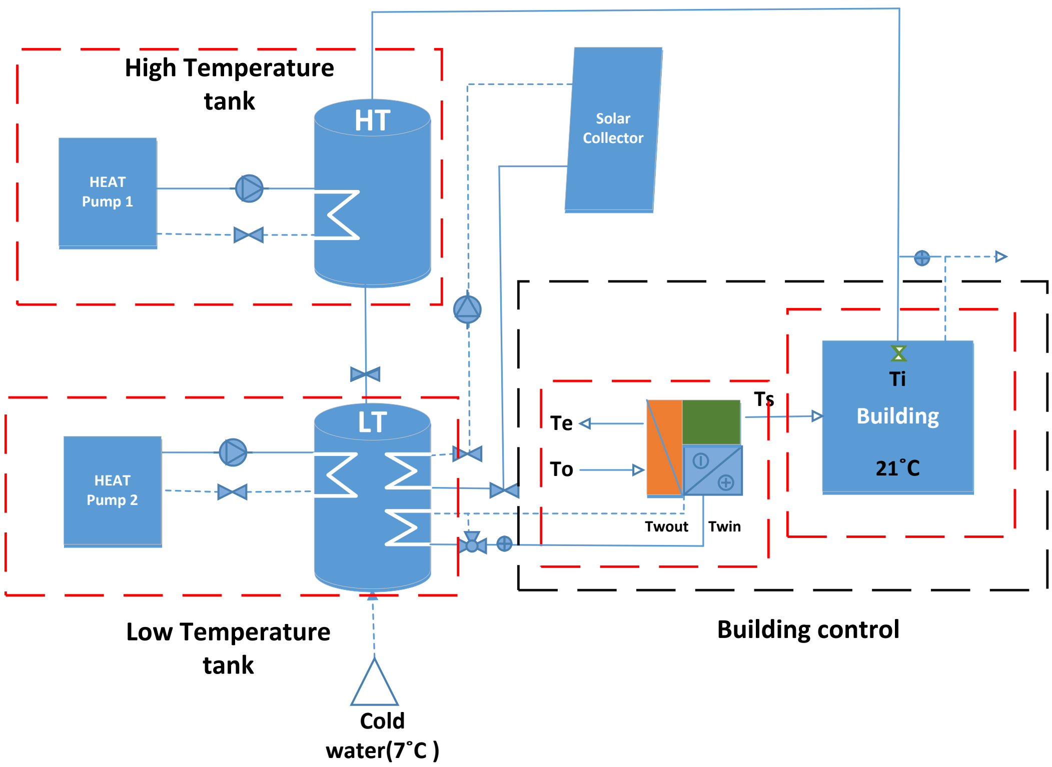


Figure 13. Schematic of the whole energy system of components

In the two tanks, low temperature tank uses for space heating and high temperature tank employs as hot water consumption. Two tanks employ different temperature individually; IDA ICE operates low temperature and high temperature tank separately for this thesis. When PI controller for the room fixes to make indoor temperature keeping as 21 ˚C, low temperature tank supplies heat for Air Handling Unit to supply energy demand for the building model. Figure 13 demonstrates how two-thermal storage tanks with heat pumps are operating and connected. For this running, temperature of three main control system is required; low temperature tank, high temperature tank with solar collector and building inner temperature with Air Handling Unit. High temperature tank keeps temperature as 60°C and low temperature tank keeps as 45°C connected to the solar collector. In addition, the temperature of building keeps temperature as constant for the thermal comfort by the Finnish building code law. Low temperature tank receives cold water from the pipeline and heat pump connected to the low temperature tank operates to keep the signified temperature with controller.

When the temperature of the low temperature tank raises up to the predicted temperature range, gate valve between the low temperature tank and the high temperature tank opens for the flow of the water for the heat transfer from the preheating tank to the domestic hot water tank. Tank considers as eight layered stratified storage; temperature of the low temperature tank is the parameter to decide for control and monitoring when to open the valve system between two tanks. With the heat pump and tank, pump system installs with gate valve for manipulating the exact COP for running. Moreover, three-way valve installs between the solar collector and Air handling unit (AHU) for controlling the flow rate for the coil and fin tube inside of solar collector and AHU. Air handling unit (AHU) system adopts the fin tube coil for the liquid flow in the view of temperature going and coming into the AHU for the heat transfer to the building. Low temperature tank is used for the radiating the building room with space heating method through the AHU. High temperature tank connects from the low temperature tank to the building and heat pump linked to the high temperature tank works for the domestic hot water supply for the building occupants. Low temperature tank activates the heat pump when solar collector cannot satisfy to work enough for letting the temperature keep as 45°C. Low temperature tank connects to the Air Handling Unit system and Air handling unit (AHU) supplies heat to the building from the tank using temperature control exchanging water flow from the pipeline. In this way, three main control system runs normally setting the various temperature of the building in constant states. For this system, how to control the lower temperature tank decides the how the room temperature is keeping constant.

Whole schematic of energy system components is described in the below figure 14 as explained previous. Control system between solar thermal and low temperature tank works depending on the outdoor weather data with solar radiation and temperature. In low temperature tank, solar thermal energy generation compensates the operating the heat pump connected to the tank system and less electricity consumption is required with auxiliary heater as top heating when it comes to ESBO plant. Solar panel connects with the pipeline between tank and solar collector. When the solar collector is used, less electricity is required than without solar collector case. Top heating uses auxiliary heater system for the solar collector warming up inside of the hot storage tank.

Heat demand required from the building and HVAC system is same, thus radiating heat demand mentioned as space heating supplies from the low temperature tank only. High temperature tank keeps temperature higher than low temperature tank for using as hot water usage inside of the building for occupants; this domestic consumption follows by the initial data from the number of occupants and their behavior profile.

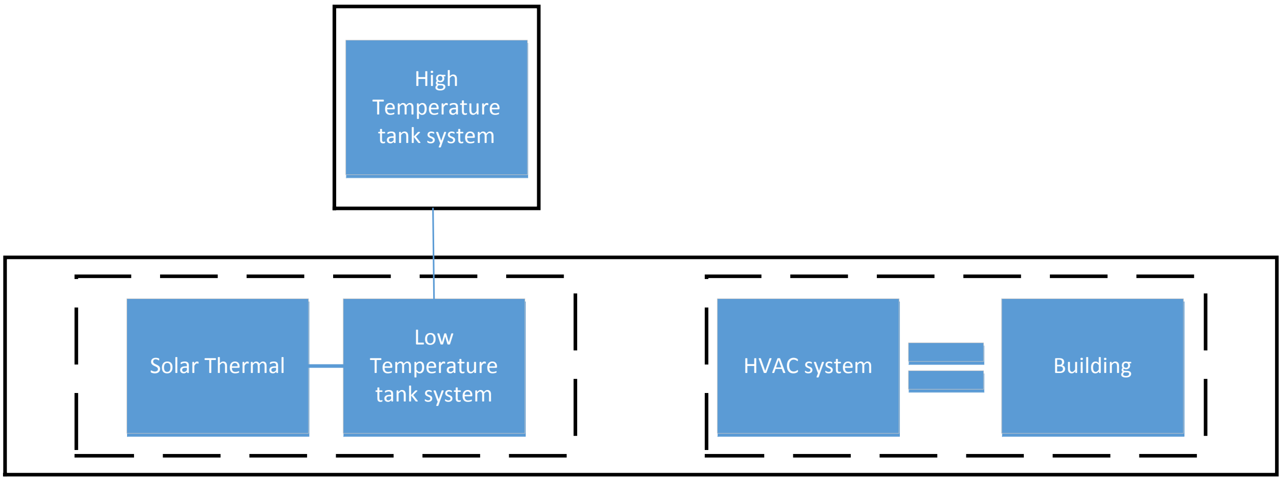


Figure 14. Schematic of operating the whole energy system for components

3. Structure of HVAC energy system

3.1 Modelling of the system components

Building the model and generating optimal energy components conducts through IDA ICE and installed wizards. As figure 15 demonstrates, initial input data show as weather data and heat demand from occupants' behavior, lighting and equipment. When IDA ICE accepts input data and analyze them and display as heat demand of the building with the usage of electricity consumption, control and optimization is done from the Matlab and result is demonstrated as the Pareto efficiency (Pareto Front) after multi objective optimization and validation is done.

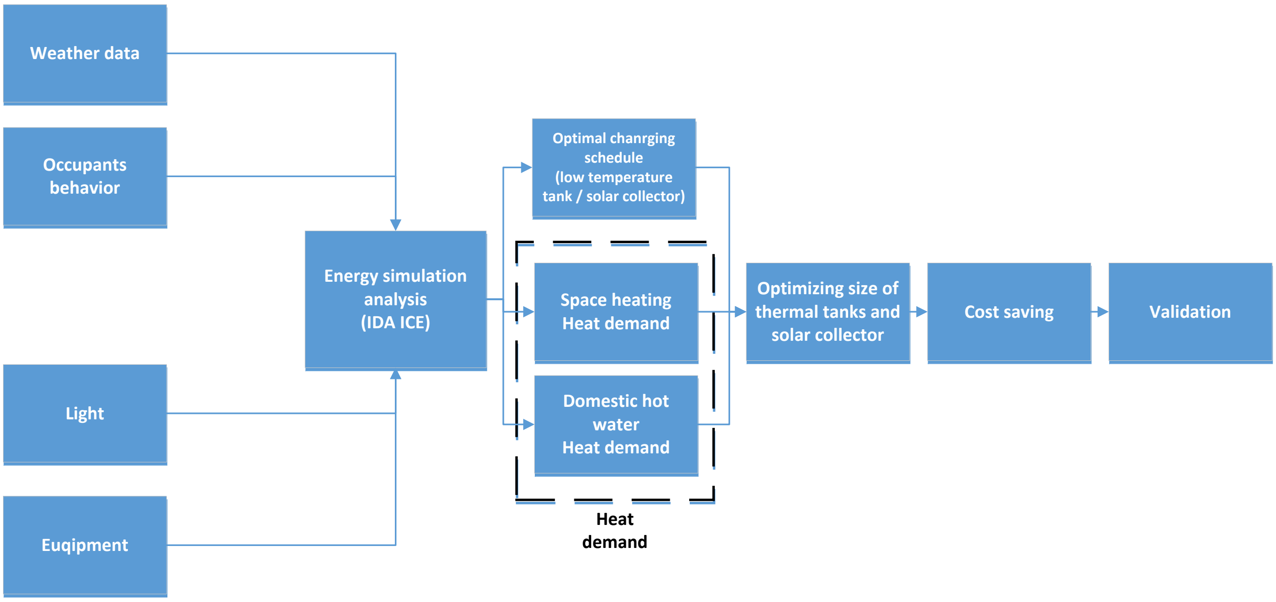


Figure 15. Work process with simulation and optimizing software

This study is based on fulfilling the energy demand of residential single-family house with two-story house. It assumes that building is generally considered to be connected two-ground source heat pump models with solar collector and Air Handling Unit (AHU) to ventilate the whole building envelop. For warming up the building envelope, two geothermal heat pumps connect separately to each thermal tank. One thermal tank uses for space heating and connected to the AHU for radiator system. Another thermal tank employs to use hot water inside of the building. In Finnish building, hot water uses for making the building warm and following the occupants' usage profile. The former thermal tank is applied to the preheating and useful for the radiation system for the building envelope. Radiating the building envelope inside requires different heat demand by the building type, massive passive, medium and lightweight.

AHU lets the inside of single family house warm up as space heating method and keeps temperature as 21°C satisfying heating demand of the inside building depending on occupancy behaviors and outdoor temperature. Hot temperature tank connects with heat pump model 1 and sends domestic hot water into the building while preheating tank plugs into the heat pump 2. Low temperature tank connects with solar collector and AHU separately and high temperature tank works for offering domestic hot water in the building by the schedule. Temperature control conducts through the whole system connected to the building and valve and water flow control is dependent on the temperature control in each case. Figure 16 explains the temperature control for the low temperature tank with solar thermal, high temperature tank and air handling unit with building cases.

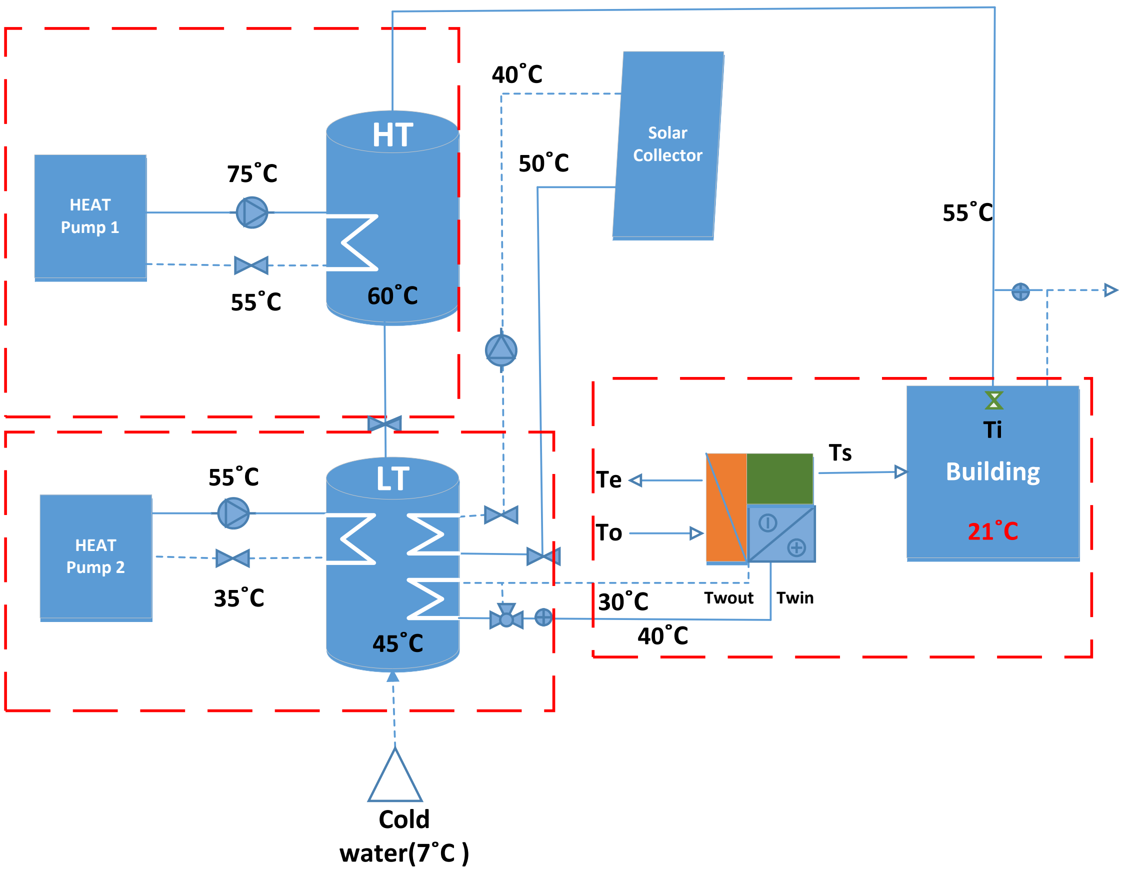


Figure 16. Schematic of HVAC system, actual product system

Solar thermal activates to supplement the usage of heat pump2 thus; operation between solar thermal and heat pump2 runs in the opposite way for temperature compensation. During summer season, when the temperature and radiation is enough for the solar thermal to collect heat, less electricity consume from the heat pump2. Temperature from the low temperature tank to the solar thermal reaches about 40°C and to the tank from the solar thermal amounts to the 50°C respectively. Mass flow rate inside of solar thermal manipulates the temperature difference of this range. Two tanks with solar collector employs in this case different from typical one tank with one solar collector in IDA ICE simulation. To get the heat demand and make optimization for this scenario, one tank only for the domestic hot water runs the simulation getting rid of radiator and space heating connection. In addition, another tank only drives for the space heating with solar collector without considering domestic hot water consumption dataset.

As results shows, utilized free energy demonstrates how energy demand from the building uses in case of domestic hot water and space heating. Domestic hot water is hot water consumption from occupants inside of building. Regardless of outdoor condition, hot water consumption has its schedule daily and monthly from the profile data of occupants. Building model requires massive passive, medium and lightweight type suitable for the various Finnish weather and circumstances. Different type of building is dealing with from the SAGA (Smart Control Architecture for Smart grids – 2012-2016) project, inside of Aalto Energy Efficiency Research Program (AEF) financed by the Aalto University. By the Alimohammadi et al. 2016. Procedure of getting the heat demand and adoption explains in the figure 17 with schematic. After building model and importing the drawing for the single-family house, simulation result implies heat demand from each case of tank and combining it works in the form of row vector inside of Matlab.

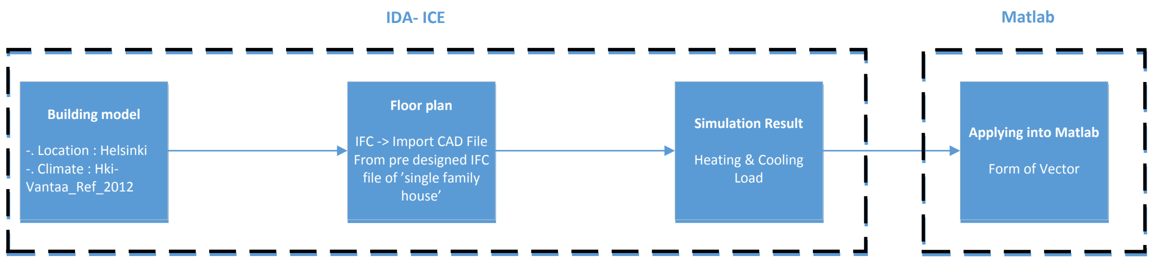


Figure 17. Process of IDA ICE operating with Matlab for getting the heat demand

After running low temperature tank and high temperature tank separately, combining cases with Matlab and optimizing tank size and solar collector area completes the task based on Life Cycle Cost. After result, validation conducts with Multi Objective Optimization (MOBO) and IDA ICE together. Before composing the control code and gathering the dataset, introducing components, which exploits in the ESBO plant, is required. Main control part is two thermal tank temperature and AHU operation, every component as Air handling unit, heat pump and two tanks with solar collector, used in ESBO plant needs information.

As discussed previous, components explains for the control with schematic in Figure 16. Main temperature control conducts through the low temperature tank, high temperature tank and the solar collector control system, energy components explain briefly before starting the control and optimization. Air Handling Unit, two geothermal heat pumps, two tanks and solar collector operation principles are studied.

3.1.1 Air Handling Unit

Air Handling Unit is the Indoor air conditioning device connected with lower temperature tank and supplying air to the building for the space heating. In Finnish weather, radiator connected to the AHU usually works during winter season in the way of space heating. It normally considers heating only ventilation method, thus sensible heat is main heat load regardless of specific latent heat in this case. Table 3 displays energy usage utilization inside of AHU. As shown in the table 3 case, humidifier does not work for loading the latent heat, only heating load calculates in the total energy generation.

kWh (sensible and latent)

Month	Heating	Cooling	AHU heat recovery	AHU cold recovery	Humidification	Fans
1	378.8	0.0	844.3	0.0	0.0	76.6
2	370.2	0.0	814.5	0.0	0.0	71.7
3	339.5	0.0	784.5	0.0	0.0	76.8
4	181.0	0.0	532.6	0.0	0.0	74.7
5	59.1	0.0	358.1	0.0	0.0	77.5
6	9.9	0.0	198.2	0.0	0.0	75.3
7	0.1	0.0	100.1	0.4	0.0	78.0
8	8.7	0.0	161.9	0.0	0.0	77.9
9	68.7	0.0	340.7	0.0	0.0	75.0
10	160.5	0.0	508.5	0.0	0.0	77.3
11	274.9	0.0	675.5	0.0	0.0	74.4
12	342.4	0.0	788.1	0.0	0.0	76.7
Total	**2193.8**	**0.0**	**6107.0**	**0.4**	**0.0**	**912.0**

Table 3. Energy generation inside of Air Handling Unit

The structure of air handling unit demonstrates in figure 18. This AHU is two-floored AHU with heat recovery system for the higher energy efficiency. Usually AHU has supply and return fan, humidifier, filter, motor to operate, heating and cooling coil for energy transfer. When the rotary heat recovery implies into the AHU, AHU saves energy and becomes more economical than normal one floored type. Heat recovery adopts the enthalpy transfer method considering sensible and latent heat together passing the airflow through the air-handling unit. Moisturized Asian countries accept sensible and latent heat recovery; this study only considers sensible heat load for the AHU operation.

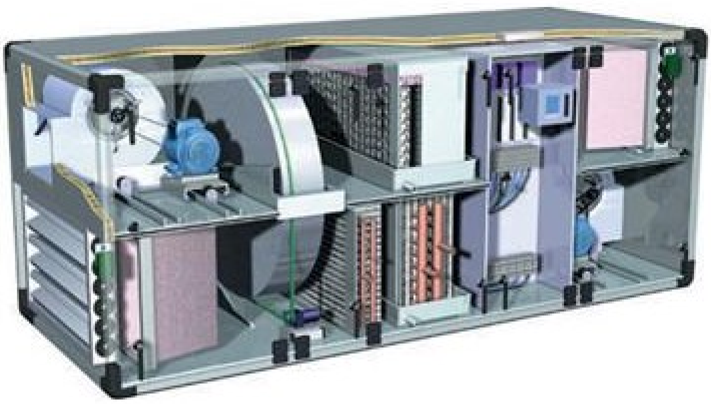


Figure 18. Inner structure of Air Handling Unit

AHU regards to connect with the radiating system in the room and low temperature tank in the system together. When low temperature tank reaches the temperature 45°C, it supplies water to the AHU opening the 3-way valve and temperature from the AHU receives energy and transfers it to the building envelope supplying the airflow. This describes in figure 19.

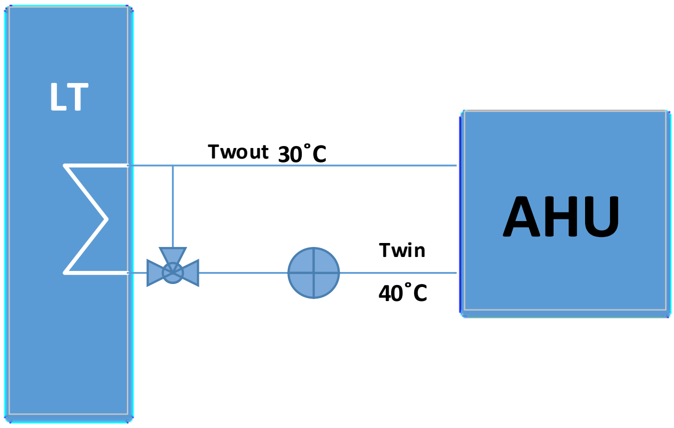


Figure 19. Air Handling Unit temperature variation from and to the tank model

In the view of heating mode energy generation, AHU does not consider the moisturized energy transfer; sensible heat demand equation completes in this research. Efficiency of AHU demonstrates depending on the temperature of inlet and outlet from the AHU.

$\eta_{AHU} = (T_{win} - T_{wout}) / (T_{win} - T_{a1})$ (12)

where

η_{AHU}	Efficiency of AHU
T_{win}	Supply air temperature of AHU
T_{wout}	Exhaust air temperature of AHU
T_{a1}	Temperature inside of AHU coil
G_{ven}	Thermal capacity of ventilation (W/K)

Thermal conductance of ventilation is depending on mass flow, density and air capacity.

$G_{ven} = \dot{m}_s * \rho * C_p$ (13)

where

$\dot{m}_s$	Mass flow of air
ρ	Density of air
C	Specific heat capacity of air

Heat demand from the AHU only considers sensible heat requirement of the room in the building model. Written again, this room is heating only. Energy balance for room calculates based on the sensible energy balance formulae.

$$\dot{Q}_{room\_sensible} = \dot{m}_s C * (T_r - Ts) \tag{14}$$

where

T_r Room Temperature

Ts Surface temperature

$\dot{m}_s$ Mass flow of air

C Specific air capacity

When mixing box used, temperature for the mixing box decides depending on the outdoor temperature and room temperature.

$$T_{mix} = (1 - r)T_o + rT_r \tag{15}$$

where

r Mixing ratio

T_{mix} Temperature in the mixing box

T_o Outdoor temperature

T_r Room Temperature

Energy balance for heating coil shows by the mixing temperature and surface temperature.

$$\dot{Q}_{Heating} = \dot{m}_s C_p (T_s - T_M) \tag{16}$$

When the indoor temperature retains as 21°C constant, heat load from the AHU displays formulae as this.

$$\Phi_{AHU} = G_{ven} * (T_s - (T_o + \eta_{AHU} * (T_i - T_o))) \tag{17}$$

When it adopts to use IDA simulation software, set point temperature of AHU is 18°C for the constant building temperature as figure 20. This is default value and can manipulate manually. Temperature inside of AHU with the outdoor temperature, AHU air flows and energy generation checks in the IDA simulation. Cooling and heating coil turn on and off by the usage of measuring in case of sensible heat and latent heat demand.

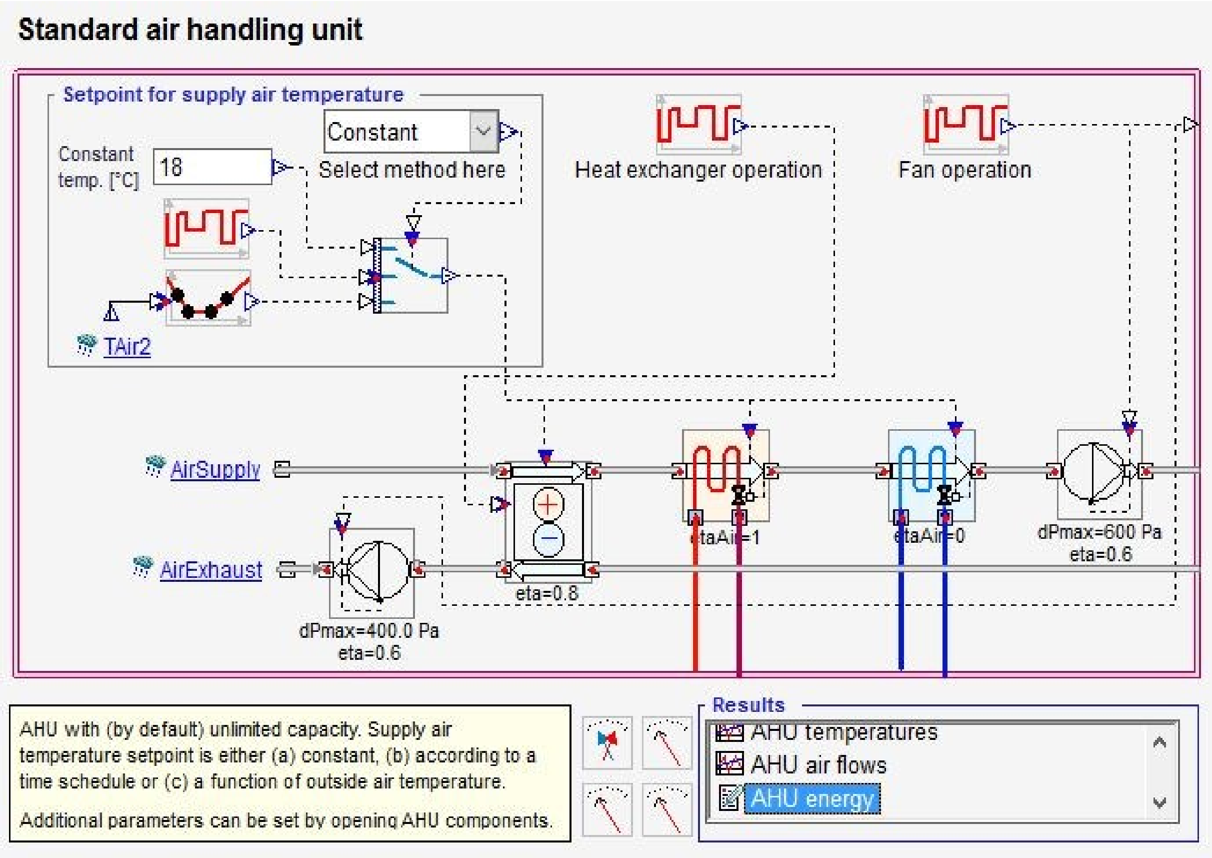


Figure 20. Set point temperature and connection inside of AHU

Heat demand from AHU is same as the room heat demand in the building envelope when it uses radiator as discussed previous model.

3.1.2 Ground Source Heat Pump

Heat pump is the device to transfer heat from absorbing at the heat source to the heat sink spontaneously. Reversed Carnot cycle (Refrigeration Cycle) uses to explain the heat pump similar as the air conditioning model. In the Mollier diagram, so called P-H (Pressure - Enthalpy) diagram, heat pump absorbs energy from the evaporator and loses energy in the heat sink generally called condenser. When heat absorption occurs evaporator, electricity consumption happens with heat pump operation and heat sink happens in the condensation. As the figure 21 demonstrates for the Refrigeration cycle, p1 is the high pressure for condensation and p2 is the lower pressure for evaporation. Heat is absorbed from a->b and work with compressor at b->c and condensation happens when pressure achieves to the p1. d-> a is the process throttling and enthalpy is set as same.

This procedure is simple refrigeration cycle and air conditioning system applies to this. However, for the HVAC system, usually heat pump considers to employ the refrigeration cycle so called reversed Carnot achieves.

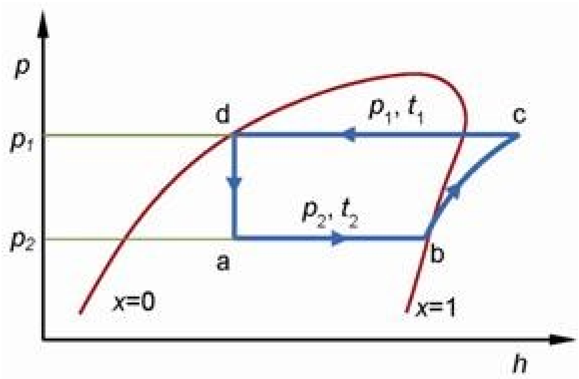


Figure 21. Refrigeration cycle with pressure and enthalpy

Four types of Heat pumps applies into the Finnish HVAC system. Ground source (Geothermal), Air to water, exhaust air and air-to-air heat pumps are those. Most energy efficient and highly electricity consumption saving and cost effective product is ground source heat pump, although total investment cost for ground source heat pump requires the most compared with other heat pump types. Table 4 from the SULPU (Finnish heat pump association) in 2013 compares prices and saving electricity by the different types of heat pump models.

Heat Pump Type	Saving kWh/a	Saving(1) € /a	Investment(2) €
Ground Source	14 000 - 17 000	1 800 - 2 200	14 000 - 20 000
Air - Water	8 000 - 13 000	1 000 - 1 700	8 000 - 12 000
Exahust Air	3 000 - 7 000	400 - 800	6 000 - 10 000(3)
Air - Air	2 000 - 7 000	250 - 800	1 500 - 2 500

Table 4. Cost and energy saving by the heat pump types (by SULPU data in 2013)

In the table, savings and investment cost are determined and reference from price explains.

1) Electricity and oil 0.13 €/kWh (electricity 13 c/kWh and oil 1.1 €/l with 80% annual operating efficiency)

2) Investment cost including installation, excluding heat delivery system

3) Including ventilation device, excluding channel installations Explanation of GSHP and two heat pump type connected separately.

According to the US EPA (United States Environmental Protection Agency), geothermal heat pumps can reduce energy consumption up to 44% compared with air-source heat pumps and up to 72% compared with electric resistance heating. Heat pump selects as the energy efficient source and usually occupies 5 % of the whole energy system by the statics of Finland, Finnish Energy association in 2013. Using higher energy efficient heat pump contributes to the better thermal effectiveness of the system. This explains how the geothermal heat pump selects to make the better energy saving system in this research.

Coefficient of performance in the low temperature tank decides by the ratio between the heating power of the ground source heat pump and its electricity consumption as below equation.

$$COP_N = \frac{\mathrm{Qout}}{\mathrm{Welectric}} \tag{18}$$

where

Q_{out} Heating power of heat pump

$W_{electric}$ Electricity consumption of heat pump

This measured COP is get from the one test point and this is assumed to be constant throughout the entire experimental period (one year in the simulation), to adopt the dataset inside simulation software, hourly theoretical COP is required.

Theoretical COP comes from the temperature difference inside of reverse Carnot cycle and generally describes with temperature between the condenser and evaporator when it uses single type heat pump not the cascade nor combined case. It explains maximum Carnot COP or refrigeration COP as equation (27) presents by the Laitinen et al.(2014).

$$COP_c(t) = \frac{\mathrm{Tcon}}{\mathrm{Tcon} - \mathrm{Teva}} \tag{19}$$

where

Tcon	Condenser temperature (K)
Teva	Evaporator temperature (K)

The hourly computed practical temperature difference for the ground source heat pump of theoretical COP_T defines as formulae (28) by one-hour time step.

$$COP_T = \frac{THSy}{THSy - THSo} \qquad (20)$$

where

T_{HSy}	Building heating system temperature, K
T_{HSo}	Heating source temperature, K

In the geothermal heat pump, T_{HSy} studies as the temperature of the fluid leaving the heat collection circuit and entering the evaporator and it usually computes with the hot tank inlet and outlet temperature connected with the heat pump.

In this thesis, Coefficient of performance (COP) with ground source heat pump is determined from the heat pump (Mitsubishi and Nibe) of SAGA (Smart Control Architecture for Smart grids – 2012-2016) project by the Niemelä et al. 2015. Heat pumps in general have the COP of 4.2 to 4.6, which places it behind cogeneration with a COP of 9. In the IDA ICE of this work, COP of 4 reciprocating geothermal heat pump is chosen to link with thermal tanks.

3.1.3 High temperature storage tank

High temperature tank assumes to supply heat to the hot water consumption in the house. It considers as high temperature tank and temperature range approaches from 55°C to 65°C. Tank is stratified fluid type with connecting domestic hot water pipe and heat pump with electric heater. Figure 22 demonstrates the energy balance from the tank to the house with heat balance schematic.

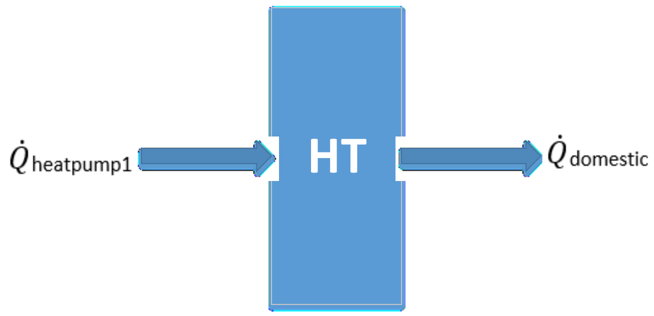


Figure 22. Heat flow of the high temperature tank

When balance equation completes in the tank model, formulae is get from the Dwivedi et al. in 2009.

$$\dot{m}_s * Cp * \frac{dTs}{dt} = \dot{Q}_{heatpump1} - \dot{Q}_{domestic} - U*A*(Ts\text{-}Ta) \tag{21}$$

where

$\dot{Q}_{heatpump1}$	Heat power from the heat pump connected by the high temperature tank
$\dot{Q}_{domestic}$	Heat load transferred to the hot water consumption
U	Tank heat loss conductance (W/m^2K).
A	Area of the thermal tank (m^2)
Ts	Instantaneous temperature of the tank (K)
Ta	Ambient temperature of the tank (K)
m_s	Mass of water in the storage tank (kg)
C_P	Heat capacity of water (J/kg*K)

Heat pump generates the heat power regularly connected to the thermal tank system. When the domestic hot water consumption load is satisfied, size of the hot water tank can optimize depending on this equation.

3.1.4 Low temperature storage tank

Low temperature tank operates between the temperature 40°C and 50°C. It links with high temperature tank, solar collector, ground source heat pump and AHU system for the space heating. It is supposed to open the valve between the two thermal tanks and high temperature tank receives water path when the temperature of low temperature tank reaches around 45°C. Solar collector gathers solar radiation and temperature during the whole year and lets the heat pump electricity consumption less to operate the low temperature tank in the static condition for the accepted temperature range. Figure 23 demonstrates the heat balance of the tank in schematic.

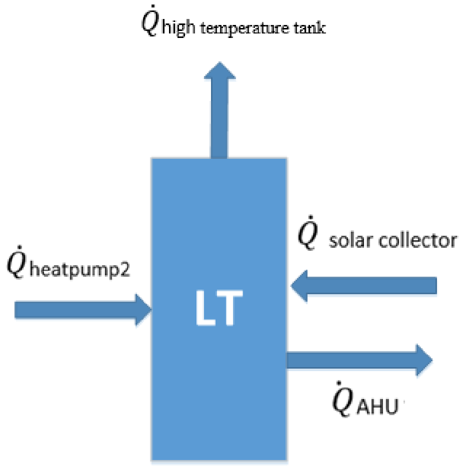


Figure 23. Heat balance of the low temperature tank

As figure shows, low temperature tank energy balance is dependent on the heat power from the heatpump2, high temperature tank, solar collector and AHU. When it comes to the formulae, equation (22) shows its relations.

$$\dot{Q}_{\text{Low temperature tank}} = \dot{m}s*C_p*\frac{dTs}{dt} = \dot{Q}_{\text{heatpump2}} + \dot{Q}_{\text{solar collector}} - U*A*(Ts\text{-}Ta) - \dot{Q}_{\text{AHU}} \qquad (22)$$

where

$\dot{Q}_{\text{Low temperature tank}}$	Heat power from the low temperature tank
$\dot{Q}_{\text{heatpump2}}$	Heat power from the heat pump connected to the low temperature tank

$\dot{Q}_{\text{solar collector}}$	Heat gain from the solar collector
$\dot{Q}_{\text{AHU}}$	Heat load transferred as radiation for space heating
U	Tank heat loss conductance (W/m^2K).
A	Area of the thermal tank (m^2)
T_s	Instantaneous temperature of the tank (K)
T_a	Ambient temperature of the tank (K)
m_s	Mass of water in the storage tank (kg)
C_P	Heat capacity of water (J/kg*K)

In the low temperature tank model, heat loss in the tank is different by the time and it can be get as iterative method by the hourly time step heat-demand data calculating as row vector. Solar collector can reduce the electricity consumption of the heat pump and this leads to the energy saving especially during the summer season.

3.1.5 Solar Collector

Solar collector is key component for the thermal tank system with solar heating. Solar thermal transforms solar energy as radiation permeates into the heat in the liquid inside of the collector. Generally, two main types of solar collector employs; Flat plate collectors and concentrating collectors. In the flat plate collector, solar absorbing surface in the plate is almost same size as the overall collector area, while concentrating collector employs small area of collector with mirror reflection to gather the solar energy. In this thesis, flat plate collector employs and it usually studies in the single-family house of the Finland.

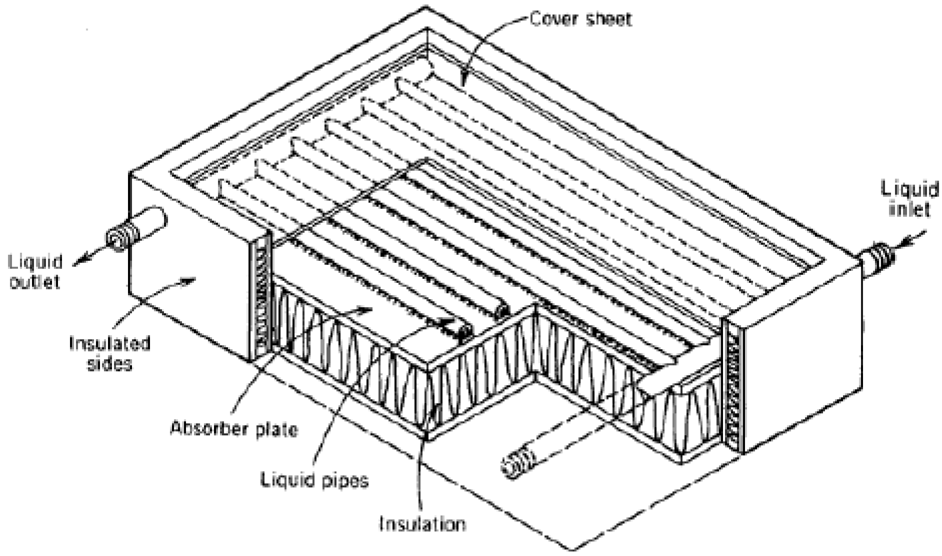


Figure 24. Flat plate solar collector whole structure

Figure 24 explains the whole structure of flat plate solar collector with inlet and outlet temperature with fluid. When the solar radiation (W/ m^2) is absorbed to the flat plate of solar thermal, solar thermal gathers it by the surface area of the collector (m^2). When the surface area of the collector receives it, transmittance coefficient through the glazing and absorption coefficient for plate considers solar rays to let it arrive and penetrate into the transparent cover of the collector. Collector heat input ($\dot{Q}_i$) regards as equation (23).

$$\dot{Q}_i = I(\tau\,\alpha)A_c \tag{23}$$

where

I	Solar radiation density to solar collectors (W/m^2)
α	Absorption coefficient of plate
τ	Transmittance coefficient of glazing
A_c	Collector area (m^2)

As the solar thermal absorbs solar heat, temperature inside the collector raises higher than the ambient temperature surrounded, it loses energy to the atmosphere as radiation and convection heat load by the overall transfer coefficient. Useful energy gain ($\dot{Q}_u$) from the solar collector presents formulae (24) with the whole energy gained from the collector and removal of this heat loss.

$$\dot{Q}_u = \dot{Q}_i - \dot{Q}_o = I(\tau\,\alpha)A_c - U_L(T_c - T_a) \tag{24}$$

where

$\dot{Q}_i$	Collector heat input (W)
$\dot{Q}_o$	Heat loss (W)
T_c	Collector average temperature (K)
T_a	Ambient temperature (K)
Ac	Absorber area (m^2)
U_L	Solar-collector heat loss coefficient (W/m^2)

Useful heat gain from the collector measures by the mass flow of the liquid inside of collector. Amounts of liquid in the collector monitors the inlet and outlet temperature in the flat plate solar thermal system.

$$\dot{Q}_u = \dot{m}_s C_p (T_{fo} - T_{fi}) \tag{25}$$

T_{fi}	Flat-panel inlet fluid temperature inside of solar collector (K)
T_{fo}	Flat-panel outlet fluid temperature inside of solar collector (K)
C_p	Liquid capacity
$\dot{m}_s$	Flow rate of fluid through the collector (kg/s)

The rate of useful heat gain extracted from the collector expresses mass flow and temperature difference between the inlet and outlet of flat plate. When the solar collector heat removal factor (Fr) introduces for the difficulty of getting collector average temperature, formulae completes with the Hottel-Whillier-Bliss Equation (26) using inner flat temperature instead of collector average one.

$$\dot{Q}_{solar} = \dot{m}_s C_p (T_o - T_{fi}) = Fr\ Ac\ [I(\tau\alpha) - U_L(T_{fi} - Ta)] \tag{26}$$

where

Ac	Absorber area (m^2)
Fr	Solar collector heat-removal factor
U_L	Solar collector-loss conductance (W/m^2)
T_a	Ambient temperature (K)

Collector efficiency can describe with the ratio of the useful energy gain ($\dot{Q}_u$) and the incident solar energy reckoning time-period.

$$\eta = \frac{\int \dot{Q}u \, dt}{A \int I \, dt} = \frac{\text{Fr Ac } [\text{I}(\tau\alpha) - \text{UL}(\text{Tfi} - \text{Ta})]}{AI} \tag{27}$$

Hottel-Whillier-Bliss Equation employs the equation; it completes the formulae as (27).

To calculate steady state solar collector for useful energy, gain with function of fluid inlet temperature and ambient temperature, mass flow rate of the water inside of collector is key parameter. It is optimization decision variables for the higher efficiency of the whole system. Solar collector works based on the demand of low temperature tank. When the solar radiation is enough to load the heat gain into the thermal tank, minimum electricity consumption is required in the heat pump model of the low temperature tank. Simulation software generates the temperature-varying model in this case to generate the cost effective model for controlling the system.

4. Control strategy method for energy system

4.1 Simulation Based Control system

Heat load requirement from the building model as space heating is depending on the control of the low storage tank and solar collector response. Domestic hot water consumption in the single-family house is based on the charging schedule of the hot water tank. In the control point of view, control system requires three main components. Two thermal tank models and control strategy between low temperature tank and solar collector. Figure 25 expresses temperature control between two tanks.

When the temperature of the low storage tank exceeds the satisfying temperature of 45°C, water flows to the high temperature tank until it approaches to the 60°C. Low temperature tank and high temperature tank applies individual geothermal heat pump, it works based on the heat demand of the tank system. To optimize the size of tanks and solar collector, three models generates for control and optimization. The system with high temperature tank only for domestic hot water consumption, system with low temperature tank only with solar collector for space heating and the system with low temperature tank only without solar collector system are included; those are named as split type models.

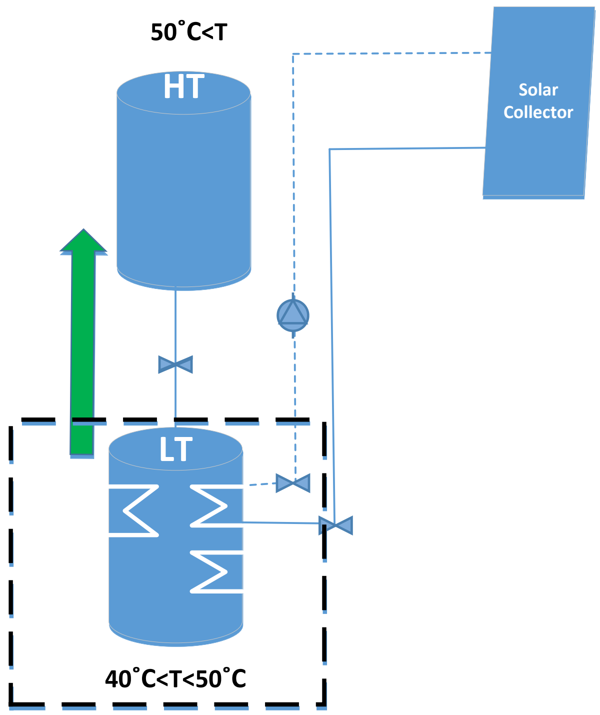


Figure 25. Control strategy between two tanks and solar collector

IDA simulation only generates the one tank with solar collector model, this split type models combine after getting separate head demand from IDA simulation separately. Massive, medium and light type of buildings are generated for domestic hot water only, space heating only with solar collector and space heating only without solar collector. All type of buildings' control strategy completes with three split models.

From the formulae (21) and (22), high temperature tank ($\dot{Q}_{\text{High temperature tank}}$) and low temperature tank ($\dot{Q}_{\text{Low temperature tank}}$) is equivalent with the $\dot{Q}_{\text{domestic water only}}$ and $\dot{Q}_{\text{space heating only with solar}}$ respectively. Split type model is required for controlling the two tank models, $\dot{Q}_{\text{High temperature tank}}$ considers only working for the hot water consumption and the $\dot{Q}_{\text{Low temperature tank}}$ is for space heating with solar collector system. Written again, formulae completes with (28) and (29).

$$\dot{Q}_{\text{High temperature tank}} = \dot{Q}_{\text{domestic water only}} = \dot{m}_s * Cp * \frac{dTs}{dt} = \dot{Q}_{\text{heatpump1}} - \dot{Q}_{\text{domestic}} - U*A*(Ts-Ta) \tag{28}$$

$$\dot{Q}_{\text{Low temperature tank}} = \dot{Q}_{\text{space heating only with solar}} = \dot{m}s * C_p * \frac{dTs}{dt} = \dot{Q}_{\text{heatpump2}} + \dot{Q}_{\text{solar collector}} - U*A*(Ts-Ta) - \dot{Q}_{\text{AHU}} \tag{29}$$

For controlling the two tank models, combining formulae decides as equation (30) and conducts with Matlab defined codes.

$$\Sigma\dot{Q} = \dot{Q}_{\text{Domestic water only}} - (\dot{Q}_{\text{Space heating only with solar}} - \dot{Q}_{\text{Space heating only without solar}}) + \dot{Q}_{\text{Space heating only without solar}} \tag{30}$$

where

$\dot{Q}_{\text{Domestic water only}}$	Heat demand from the model for domestic hot water only
$\dot{Q}_{\text{Space heating only with solar}}$	Heat demand from the model for space heating only With solar collector
$\dot{Q}_{\text{Space heating only without solar}}$	Heat demand from the model for space heating only Without solar collector
$\Sigma\dot{Q}$	Total sum of actual heat demand between two tanks

Fulfilling the requirement of actual heat demand between two tanks, formulae (25) employs. In the low temperature tank, the residual energy from the tank is determined by the heat generated vector from the IDA model of space heating only with solar model ($\dot{Q}_{\text{spaceheating only with solar}}$) and the space heating only without solar model ($\dot{Q}_{\text{space heating only without solar}}$). High temperature tank keeps 60°C after preheating the low temperature tank of 45°C, $\dot{Q}_{\text{domestic water only}} - (\dot{Q}_{\text{spaceheating only with solar}} - \dot{Q}_{\text{space heating only without solar}})$ is the pure heat demand of high temperature tank when preheated heat demand from low temperature tank is get rid of. Actual total sum of heat demand between two tanks could be calculated adding the $\dot{Q}_{\text{domestic water only}} - (\dot{Q}_{\text{spaceheating only with solar}} - \dot{Q}_{\text{space heating only without solar}})$ and $\dot{Q}_{\text{space heating only without solar}}$. This name as connected case, which considers the control strategy between two tanks employing the balance equation. Non Connected case is simple gross amounts between $\dot{Q}_{\text{spaceheating only with solar}}$ and $\dot{Q}_{\text{domestic water only}}$. Connected case and non-connected cases are considered to show the control result when it comes to compare the dataset for optimization. In this control strategy, temperature is main parameter to make preheating and the let the valve open water flows between two tanks system. When temperature exceeds approximately over 50°C, tank for domestic hot water usage operates. Final temperature decides by the iterating the previous tank temperature each time step by the Euler implicit method.

For the control strategy, how each component parameter as tank and solar collector temperature, collected heat, COP, energy utilization affects to the low temperature tank and high temperature tank attributes to the operation and total sum in the connected case. Space heating only tank with solar collector and space heating only tank without solar collector is considered as low temperature tank control, domestic hot water only tank is high temperature tank control and the last, control between solar collector and low temperature tank shall be explained.

4.1.1 Low temperature storage tank control

Low-temperature tank control has two simulation models. One is space heating only tank model with solar collector and the other is space heating only tank model without solar collector. For setting up, in the IDA ICE ESBO plant, getting rid of connection pipe of domestic hot water usage and setting schedule of domestic hot water consumption profile as zero value is main task. For the space heating only with solar collector model in figure 26, solar collector setting temperature is dependent on the PI control and it manipulates as 5°C. In addition, the thermostat temperature for the variable set point, it decides as 95 °C as maximum.

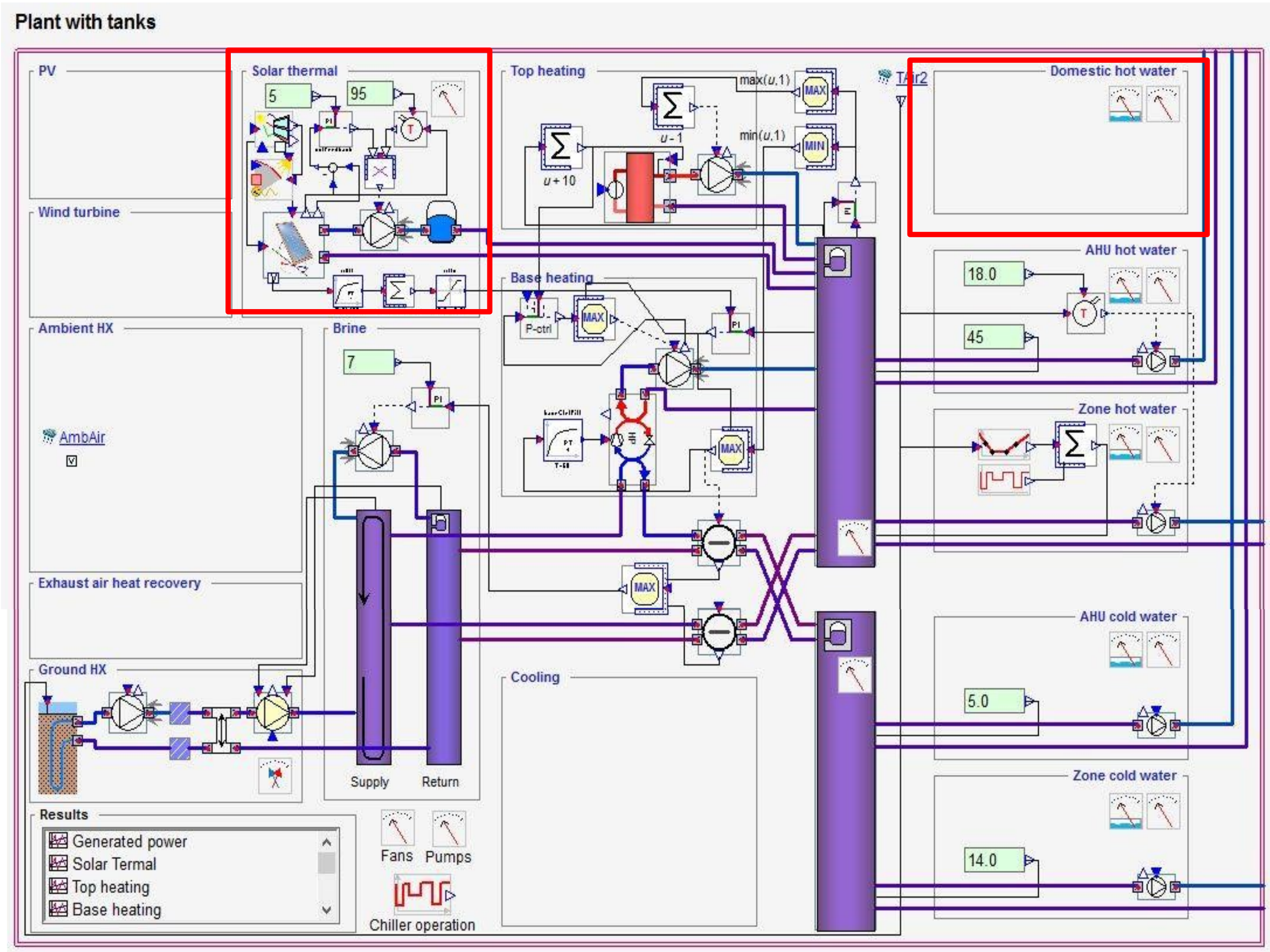


Figure 26. Space heating only tank with solar collector model

In case of the space heating only without solar collector model in figure 27, solar collector pipe connection deletes as red box shows. In addition, domestic hot water consumption usage is not available same as Figure 26.

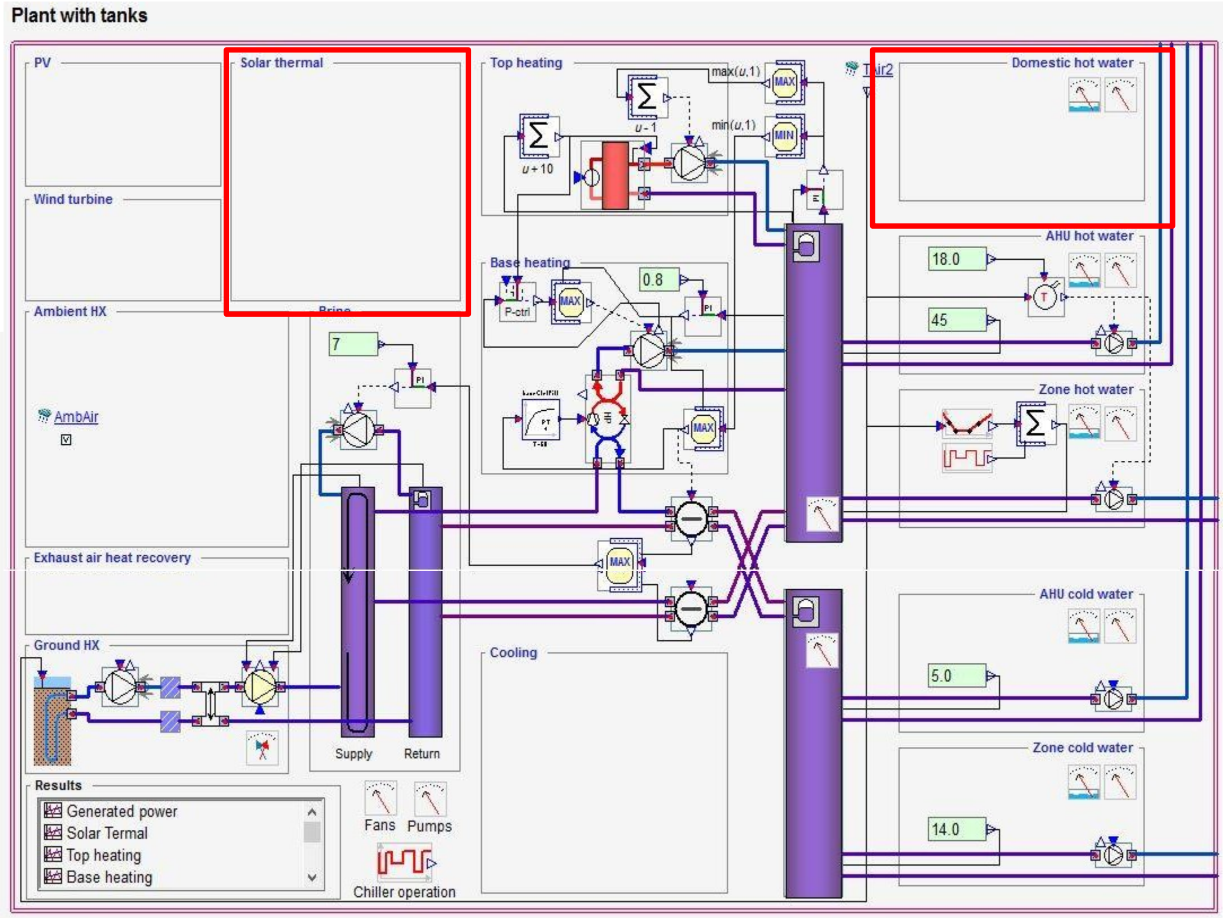
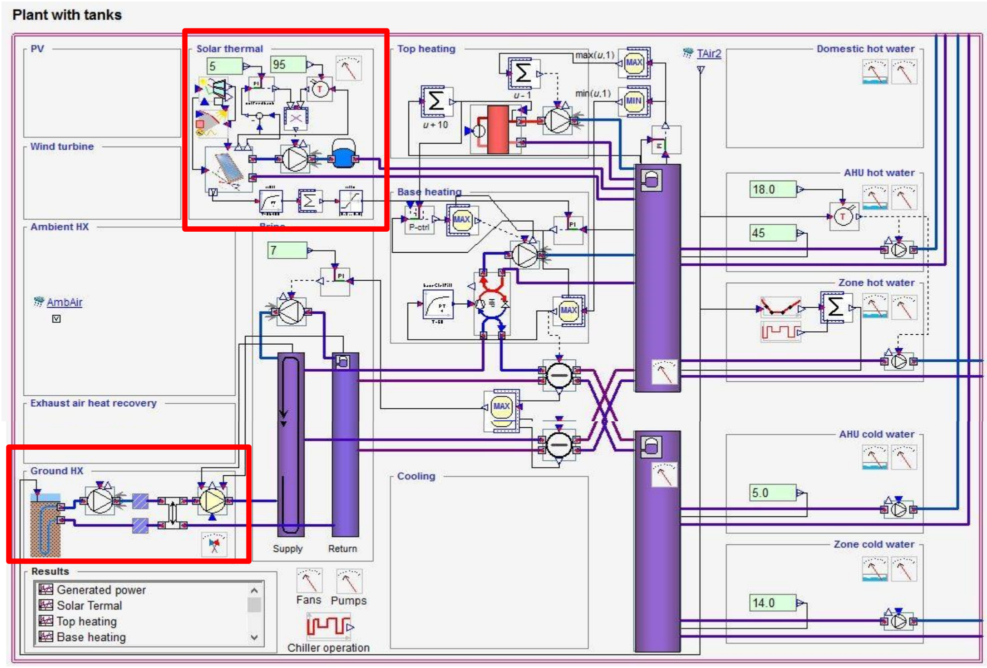
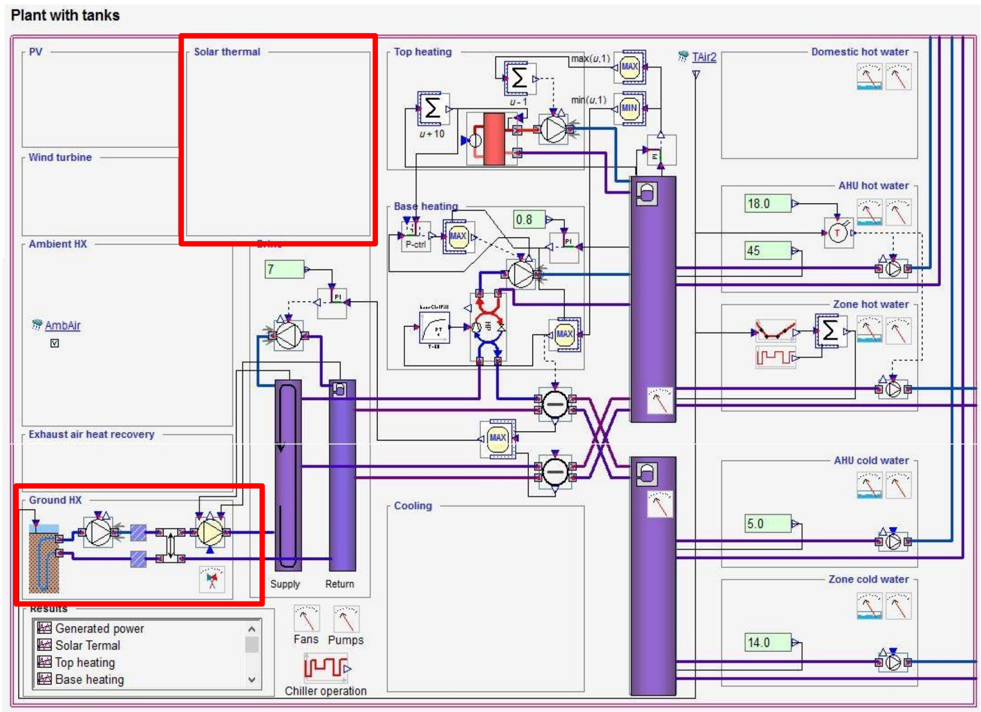


Figure 27. Space heating only tank without solar collector model

Figure 28 is the ground heat exchanger in the ESBO plant, adopting borehole and pipe type. As presented, heat exchanger directly links to the ground source heat pump and mass flow, thus heat collected in the exchanger is object to the heat pump power operation and working hour. Space- heating only with solar collector or without solar collector model demonstrates energy generation and mass flow in the result section to show the correlation with heat pump operation.



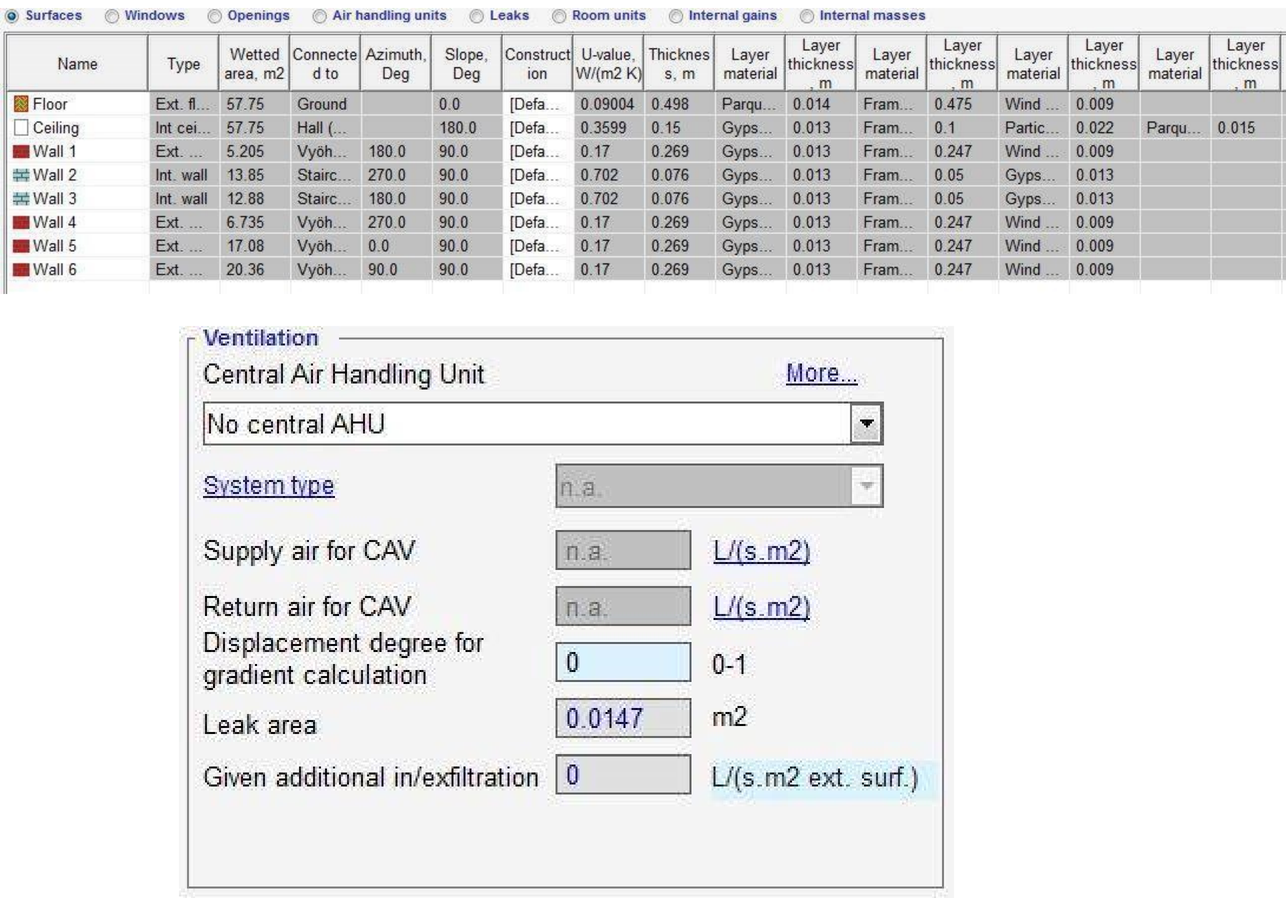


28. Heat exchanger component
In case of Space heating only tank with / without solar collector model

While heat pump works only for the space heating, how to control the low temperature tank is dependent on the operation of solar collector and energy balance of the inner tank state. Temperature control conducts monitoring its variation in the tank and connection with solar collector. In the low temperature tank model, space heating with solar collector and space heating without solar collector samples gather separately in massive medium and light building models; tank size changes from 0.5 m^3 to 2 m^3 , solar collector area comes from 1 m^2 to 10 m^2. Thus, 40 samples for space heating with solar collector and 4 samples for solar collector without solar collector model. Three different building insulation types are included, 132 samples generate for control strategy and optimization later on.

4.1.2 High temperature storage tank control

High temperature tank only works for the hot water consumption. From the normal IDA one tank simulation, getting rid of space heating radiator and AHU is essential to generate the domestic hot water only model. From the whole envelope of the building model, central Air handling unit deletes blocking to offer the radiation into the building as figure 29 shows.



Name	Type	Wetted area, m2	Connected to	Azimuth, Deg	Slope, Deg	Construction	U-value, W/(m2 K)	Thickness, m	Layer material	Layer thickness, m	Layer material	Layer thickness, m	Layer material	Layer thickness, m	Layer material	Layer thickness, m
Floor	Ext. fl...	57.75	Ground		0.0	[Defa...	0.09004	0.498	Parqu...	0.014	Fram...	0.475	Wind ...	0.009		
Ceiling	Int cei...	57.75	Hall (...		180.0	[Defa...	0.3599	0.15	Gyps...	0.013	Fram...	0.1	Partic...	0.022	Parqu...	0.015
Wall 1	Ext. ...	5.205	Vyöh...	180.0	90.0	[Defa...	0.17	0.269	Gyps...	0.013	Fram...	0.247	Wind ...	0.009		
Wall 2	Int. wall	13.85	Stairc...	270.0	90.0	[Defa...	0.702	0.076	Gyps...	0.013	Fram...	0.05	Gyps...	0.013		
Wall 3	Int. wall	12.88	Stairc...	180.0	90.0	[Defa...	0.702	0.076	Gyps...	0.013	Fram...	0.05	Gyps...	0.013		
Wall 4	Ext. ...	6.735	Vyöh...	270.0	90.0	[Defa...	0.17	0.269	Gyps...	0.013	Fram...	0.247	Wind ...	0.009		
Wall 5	Ext. ...	17.08	Vyöh...	0.0	90.0	[Defa...	0.17	0.269	Gyps...	0.013	Fram...	0.247	Wind ...	0.009		
Wall 6	Ext. ...	20.36	Vyöh...	90.0	90.0	[Defa...	0.17	0.269	Gyps...	0.013	Fram...	0.247	Wind ...	0.009		

Figure 29. Insulation of the whole spaces and domestic hot water only model generation

In this method, tank size from 0.5 m^3 to 2 m^3 demonstrates, 12 samples adopt for the massive, medium and light type of building material insulations.

4.1.3 Solar collector and low temperature storage tank control

Solar collector works based on the radiation and temperature of the weather data; low temperature tank receives energy from the solar collector and controls the tank with temperature variation. Energy balance inside of low temperature tank requires temperature control with 45 °C, when temperature becomes lower, energy gains from solar collector. Figure 30 shows the temperature control between the low temperature and the solar collector.

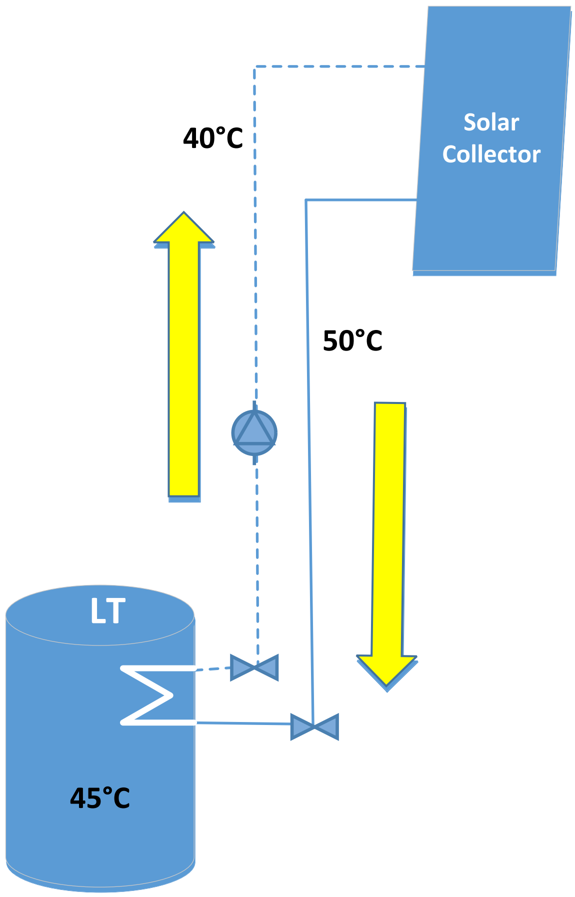


Figure 30. Temperature control between solar collector and low temperature tank

Tank connected to the solar collector shows significant result from the tank without solar collector model. Low temperature tank compensates energy from the solar collector and keeps the tank temperature as 45 °C. When the temperature goes lower than 40 °C, inlet valve opens and the solar collector generates energy by the panel and liquid flow gets back into the tank with temperature of 50 °C. Solar collector and low temperature tank control is primary control strategy in the low temperature tank case.

4.2 Artificial Neural Network (ANN) for the structure of the decision variables

In this thesis, the main target is optimizing the size of thermal system component according to energy performance and life cycle cost. The performance of the system defines based on annual heat collected by thermal solar system. The life cycle cost is described by investment, maintenance, escalation and inflation rate. Before optimizing the whole energy system, three main control is finished and space heating only tank with solar collector, space heating only tank without solar collector and the domestic hot water only models generate. For combining these split systems, Artificial neural network (ANN) is done for the space heating only tank with solar collector model to get the input vector for the energy generation in the heat pump and solar collector, both connected to the low temperature tank.

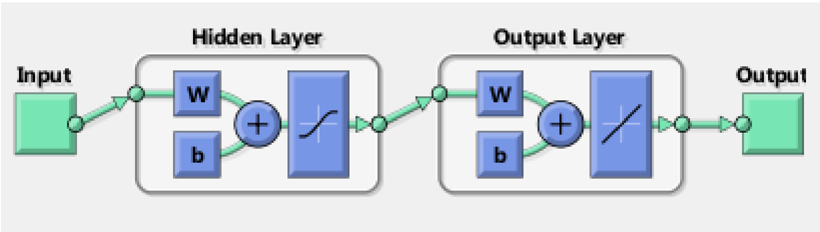


Figure 31. Neural network structure and analysis

Six different neural network models develop to calculate the annual collected solar heat and heat pump energy usage. Each of two neural network models for heat pump electricity consumption and thermal solar energy generated assign for one type of building. Since in the thesis three type of buildings as lightweight, medium and massive are studied, thus total number of six neural networks need. Neural network has input and output vector with neuron systems inside.

Inner structure of neural network deals with number of hidden layer, number of neurons in hidden layer and type of activation function in each neuron. It predefine input and output layer vectors according to number of decision variables and the target value. In this thesis, decision variables are size of thermal solar collector and volume of the tank. Therefore, the number of neurons in input layer are set as two. For output, the total heat collected by the system considers as one neuron in output layer. For activation function, in hidden layer and input layer, sigmoid function selects as most conventional function.

In output layer, sign function form the results of neural network. The main task for finding the right structure of neural network does not have specific rule. The number of hidden layer and corresponding neurons define with try and error process following the Levenberg–Marquardt algorithm (LMA). It means it checks different number of hidden layer and neurons with training data set and that structure which gives the lowest shall select as final structure.

Network initializes by setting all its weights to be random number between -1 and +1. Forward pass calculation processes from the target to get the actual value. Error of each neuron is essentially Target – Actual Output. This error is then mathematically to change the weight and bias in such way that error goes smaller. The error of network evaluates with mean square error and correlation between output and reference data. The mean square error deals with general accuracy of model and correlation describes how the output and reference data have similar trend. For instance, correlation 0 means no correlation and 1 means high performance of model. Training data set in this thesis include 40 samples for each type of building in the space heating only tank with solar collector model case. 70% of training data set is used in training and the rest of 15% each samples are implemented in validation and testing the model.

Figure 32 demonstrates how IDA simulates energy generation and artificial neural network operates for the parameters of heat pump and solar collector. Obtaining the utilized energy from the IDA simulation and applies to the form of input layer inside of ANN contributes to make the new structure for the optimization (NSGAII) in the scope of the suitable solutions in decision variables.

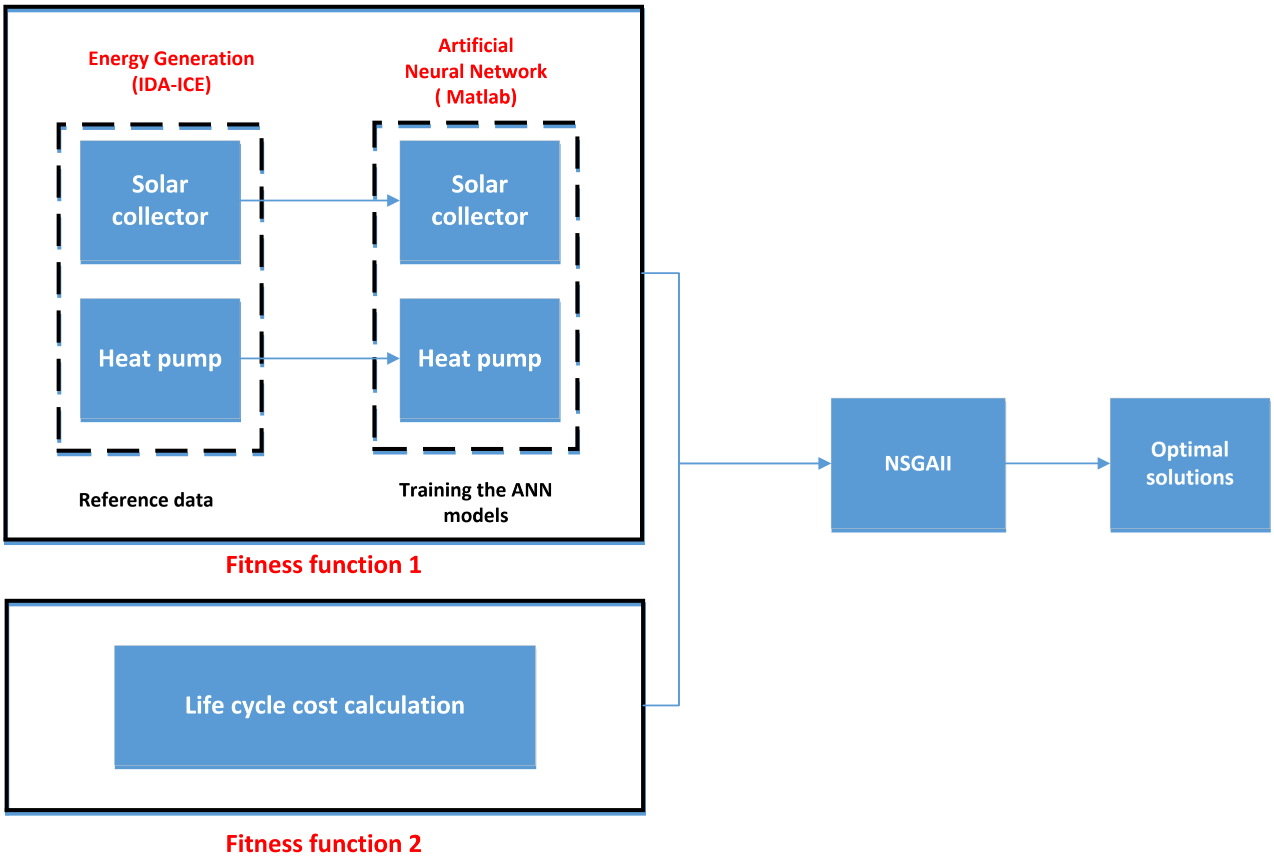


Figure 32. How ANN works based on IDA and Matlab Contribution to the Multi objective optimization

Fitness function from the ANN and function from the Life Cycle Cost (LCC) decides as the objective functions to organize the multi objective optimization. From the whole 144 samples considering light, medium and massive building type, each type of building model generates 48 samples as discussed previous. Domestic hot water only tank has 4 samples (Tank size : 0.5m^3, 1m^3, 1.5m^3, 2m^3), space heating only without solar collector also gets 4 (Tank size : 0.5m^3, 1m^3, 1.5m^3, 2m^3), while space heating only model with solar collector produces 40 samples (4 tank samples with 10 amounts of solar collector area). ANN structure is studied for the space heating only tank with solar collector using the IDA simulation, as the reference data for other datasets are simple except of space heating only with solar collector tank models.

5. Cost optimal solution method in energy building

Deciding the fitness functions to get the optimal size of solar collector and tank relates with the Life Cycle Cost (LCC) of components and less electricity consumption in the geothermal heat pumps. Cost of components and electricity usage in the heat pumps work as objective functions respectively inside of optimization in the way of Non Sorting Genetic Algorithm II (NSGA II). The definition of life cycle cost and the multi-objective optimization methods are studied and the result comes out with the coded Matlab software.

5.1 General explanation of Life Cycle Cost

For life cycle cost (LCC) analysis the main parameter considers as investment cost, maintenance cost and profit from energy. The life span for the LCC analysis defines as 20 years so no cost for renovation assigns. The main components for LCC calculation are hot water storage tank and thermal solar panel. The prices of these components extracts based on Finnish market data. The price for thermal solar collector includes cost of installation, panel, pump, pipes, control system and expansion chamber. The price for hot water storage tank covers the installation, tank and heat exchangers. The required parameters for LCC analysis presents in table 7. These parameters are interest rate and inflation factor. Based on mentioned factors the following parameters computes with below formulae.

Real interest rate calculates by equation (31).

$$r = \frac{(i-f)}{(1+f)} \tag{31}$$

where

i	Nominal interest rate
f	Inflation rate

Escalated real interest rate presents by equation (32).

$$r_e = \frac{(r-e)}{(1+e)} \tag{32}$$

where

r	Real interest rate
e	Escalation rate

Present value factor of annual maintenance cost defines by equation (33).

$$a'_n = \frac{1-(1+r)^{-n}}{r} \tag{33}$$

where

r Real interest rate

n Holding period of investment

In the end the present value factor of annual energy cost calculates by equation (34).

$$a''_n = \frac{1-(1+r_e)^{-n}}{r_e} \tag{34}$$

where r_e is escalated real interest rate and n is again holding period of investment.

Nominal interest rate	3 %
Inflation	2.0 %
Escalation for energy prices	1.0 %
Real interest rate (equation 4)	1.0 %
Escalated real interest rate (equation 5)	1.0 %
Holding period of investments	25 a
Running time period of annual maintenance costs	23 a
Present value factor of maintenance costs (equation 6)	18.33a
Present value factor of energy costs (equation 7)	22.10 a

Table 5. Applied parameters in LCC analysis

Depending on the Table 5 and formulae employed before, cost of two components, solar thermal collector and storage tank generates.

5.2 Multi Objective optimization method

The goal of the optimization is finding the best solution to minimize the price of components for the decision variables. There are several search methods for the best-optimized solution with target functions. In building energy optimization, decision variables are vectors of system components.

Element of components are

1) Area of Solar collector
2) Size of two tanks

When the objective function defines as F(x), constraint functions are G(x) and H(x), formal definition of optimization studies as follow;

$\mathrm{Min}\{F(x)\}$

$x \in R^n$

Subject to

$Gi(x) = 0 \quad i = 1,2,\ldots,m$

$Hi(x) = 0 \quad i = 1,2,\ldots,p$

where

$x = (x_1,x_2,\ldots,x_n)^T$

Here, the x vector has decision valuables for multivariate problems and best combinations found from the optimization studies.

Multi objective optimization is more general case than single objective optimization. Conflicting objectives make compromise solutions with the method known as Pareto front. The conventional way to express the multi-objective optimization problem is as,

$\mathrm{Min}\{Fi(x) = F_1(x), F_2(x)\}$

Subject to

$Gj(x) \geq 0 \quad j = 1,2,\ldots,J$

$Hk(x) = 0 \quad k = 1,2,\ldots,K$

where

$x = (x_1,x_2,\ldots,x_n)^T$

where Fi (x) deals with objective functions, here the price of components and the energy generated from the heat pump while Gj (x) and Hk (x) are constraint functions. x1 and x2 are decision variables as area of solar collector and size of tank.

Different variety of techniques consider for multi objective optimization. Non-dominant sorting genetic algorithm II (NSGA II) is the well-known method in multi objective optimization and shall adopt in this thesis.

5.2.1 Non Dominant Sorting Genetic Algorithm II (NSGA II)

The genetic algorithm (GA) is a search technique used in computing to find true or approximate solution for optimization and search problems. GA categorizes as global search heuristics. GA is a particular class of evolutionary algorithm that use techniques inspired by evolutionary biology such as inheritance, mutation, selection, and crossover (also called recombination). The evolution usually starts from a population of randomly generated individuals and happens in generations. In each generation, the fitness function of every individual in the population evaluates and multiple individuals selects from the current population and modifies to form a new population. The new population uses in the next iteration of the algorithm. The algorithm terminates when either a maximum number of generations has produced, or a satisfactory fitness level has reached for the population.

GA name indeed is an emphasis on motivation of genetic optimization algorithm based on improving the individuals by manipulating of their genotype. GA is one of the most popular technique in evolutionary computation research. In genetic algorithm the candidate solution is presented as string and each position in the string is considered to represent a particular feature of an individual. In better words, the value stored in that position represents how that feature is expressed in the solution. Thus, variation of the members of the string are expected to improve the solution. The changes in candidates is applied by means of cross over and mutation. In cross over two strings are used as parents and new individuals are formed by swapping a sub-sequence between the two strings while in mutation the single member of the string is replaced with new one as figure 33.

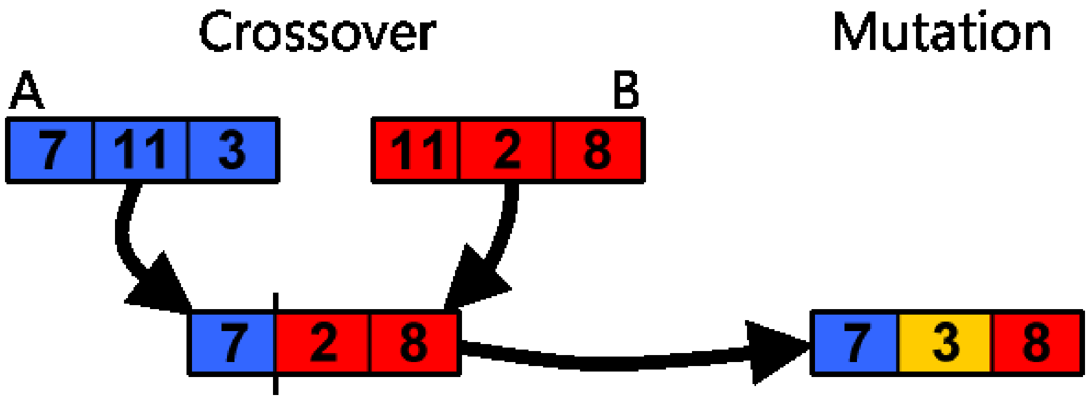


Figure 33. Crossover and mutation operators in Genetic Algorithm

(From PHP coded site about GA, www.abrandao.com)

By applying these operators, great variety develops to solve design optimization problems including discrete design parameters and then real parameter optimization problems. In genetic algorithm after defining number of variables (number of cells in solution strings) and determining the upper and lower boundaries for each variable, number of members in population defines. Then for two main operators as cross over and mutation, the percentage of probability describes to show how often each operators shall perform.

There are two basic parameters of GA as crossover probability and mutation probability. If there is no crossover, offspring is exact copy of parents. If there is a crossover, offspring makes from parts of parents' chromosome. The crossover probability could vary from 100%, which means all offspring makes by crossover to 0%, which means whole new generation makes from exact copies of chromosomes from old population. In terms of mutation if mutation probability assigns as 100%, whole chromosome changes, if it defines as 0%, then nothing is changed. Mutation should prevent the changing of procedure of GA into local extreme.

NSGAII extends version of genetic algorithm for multi objective problems. This method uses the same tools for improving the population in each generation as cross over and mutation. Nevertheless, in NSGAII two new concept applies to handle multi objective problems. The first one is non-dominated sorting which based on given ranking to each member of population defined non-dominated members. The next one is crowding distance, which in simple word defines the distance between optimal solutions in Pareto front to cover as much as possible as all optimal search space. These two concepts show in figure 34.

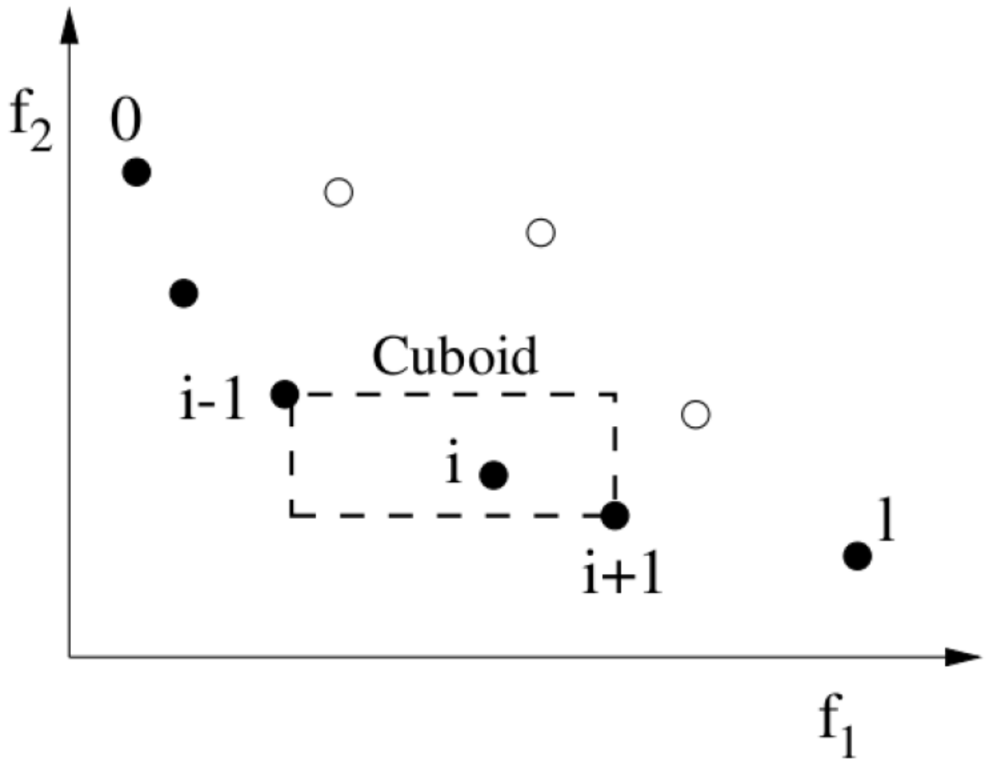


Figure 34. Application of crowding distance and non-dominant sorting in NSGAII

In Figure 34, the black nodes are the set of non-dominated members of the ongoing generation. It means that in compared with white nodes; black nodes have better value in both defined objective functions. Also by using the crowding distance, the density of best solution (black nodes) are defined in the way that solutions are located in proper distance and cover all Pareto region.

6. Validation and Discussion

Control strategy and optimization conducts with two tank models with two heat pumps. Before getting the result dataset, validating the model with one tank simulation with optimization software is required. Two neural networks train with simulation based on IDA ICE medium type of building in the one tank model at ESBO plant. The multi objective optimization carries out by using these neural networks to find the set of optimal solutions. The achieved results compare with multi objective optimization with using the IDA-ICE and MOBO (Palonen et.al. 2013).

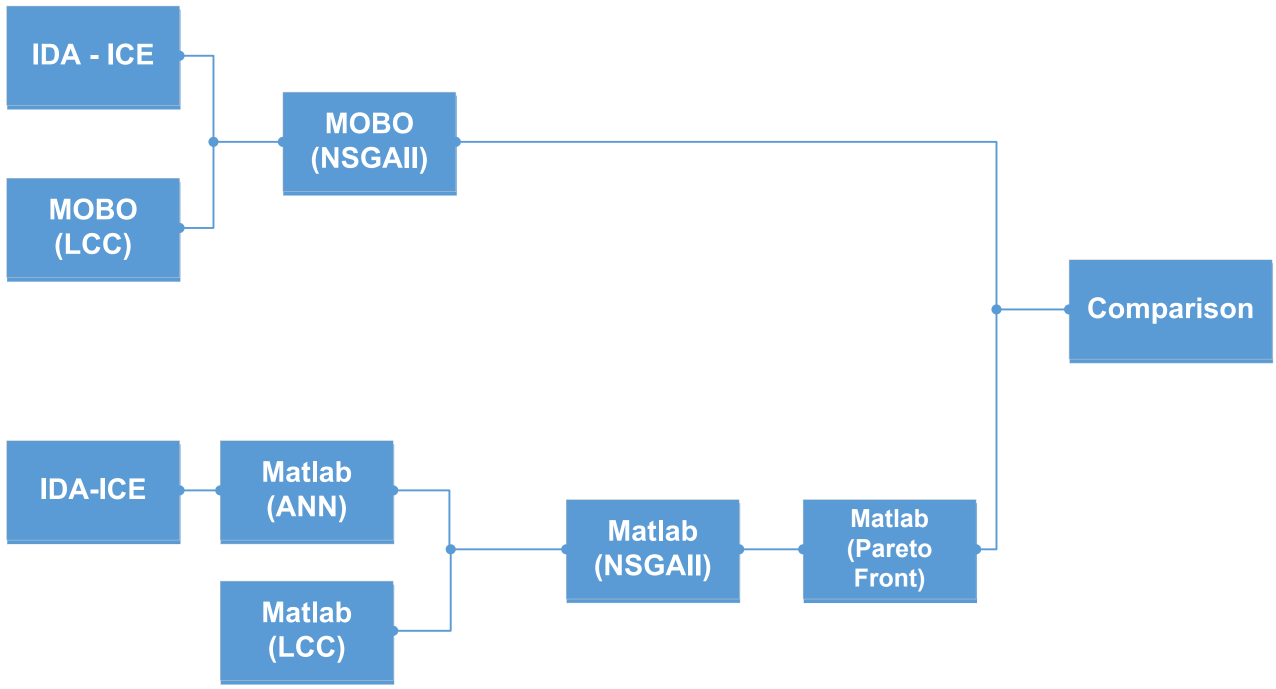


Figure 35. Result comparison between ANN-Matlab and the IDA-MOBO combination

Schematic 35 demonstrates how two different results compare with. Thesis outlines the IDA ICE and Matlab combination for getting the same result from the IDA and MOBO correlations. Two thermal tank models generate from the IDA ICE and combine by the control strategy inside of Matlab codes; multi objective optimization with the NSGA II from Matlab studies. Same process does from the one tank model with medium type of building; datasets validate from the IDA and MOBO combination with NSGA II optimization. Figure 36 shows the result of Pareto efficiency with the two functions of life cycle cost and the annual heat energy usage. In the optimization with MOBO, the number of population is set as 16 and number of generation selects as 65. In case of optimization with using the neural network, the number of population defines as 50 and number of generation assigns as 100.

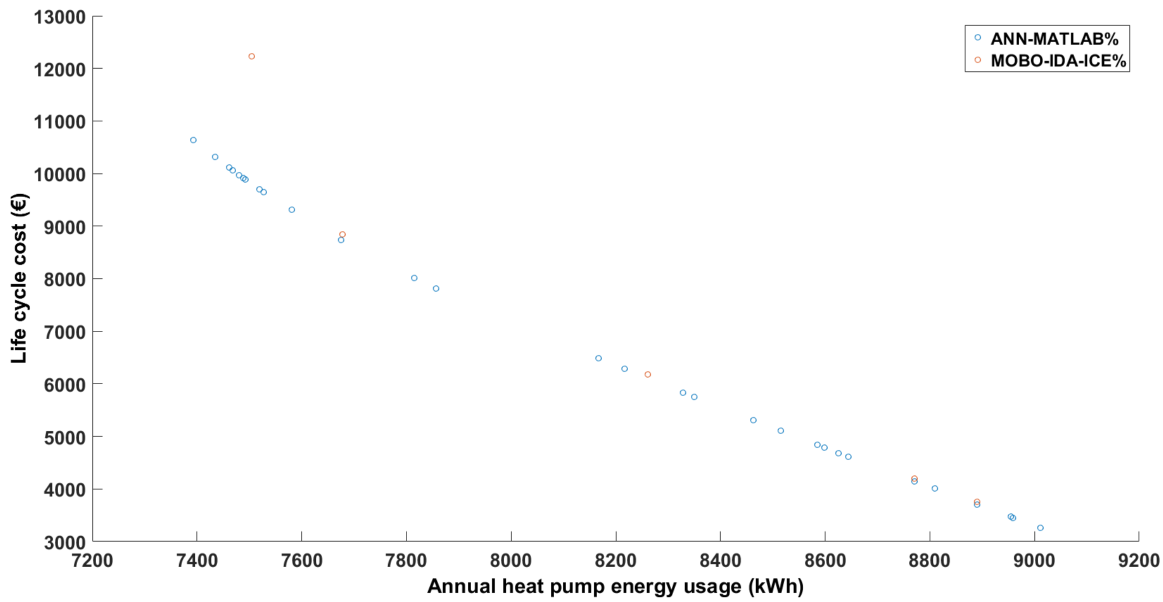


Figure 36. Pareto Front result comparison between the ANN-Matlab and MOBO-IDA

Pattern between two methods correspond in the same pace, the suggested method is reliable for finding the optimal solution.

7. Result

Generating the space heating only tank with solar collector, space heating only without solar collector and domestic hot water models adopt to the artificial neural network and optimization. Optimization result studies with Non Sorting dominant genetic algorithm method using multi- objective optimization case. Cost of the solar collector and heat pumps decides by the Life Cycle Cost (LCC) function and the energy generation of heat pump usage compares for the optimal selection of the suitable tank. Furthermore, solar collector sizes decide by the Pareto efficiency curve. When solar collector compensates the heat pump usage, energy utilization inside of heat pump shrinks to the minimum. The goal of this thesis is satisfying the two objective functions mentioned above. NSGA II uses dataset from the artificial neural network (ANN) and control code defined for connecting low temperature and high temperature tank. Influence of economic parameter as interest rate changes from 3% to 9% when it comes to the LCC calculation and plotting.

7.1 Control strategy result

Simulation employs two-tank system connected into the heat pumps separately. Usually, normal one tank model shows temperature variation as figure 37. There are 8 layers inside of tank and 1st layer at the bottom of the tank (figure 38) is connected to the space heating temperature for the radiating the building envelope. 8th layered temperature inside of stratified tank (figure 39) is used for the domestic hot water consumption of the house. It is generally higher than the temperature for space heating.

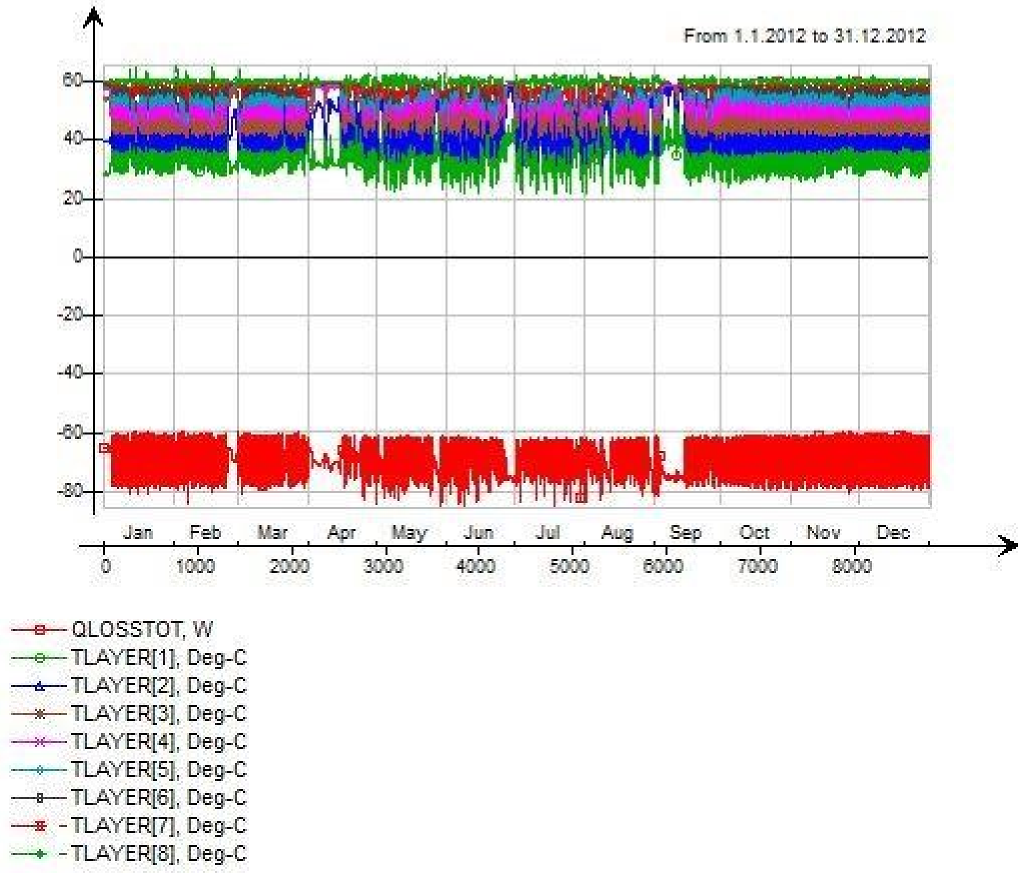


Figure 37. Temperature variation inside of stratified tank

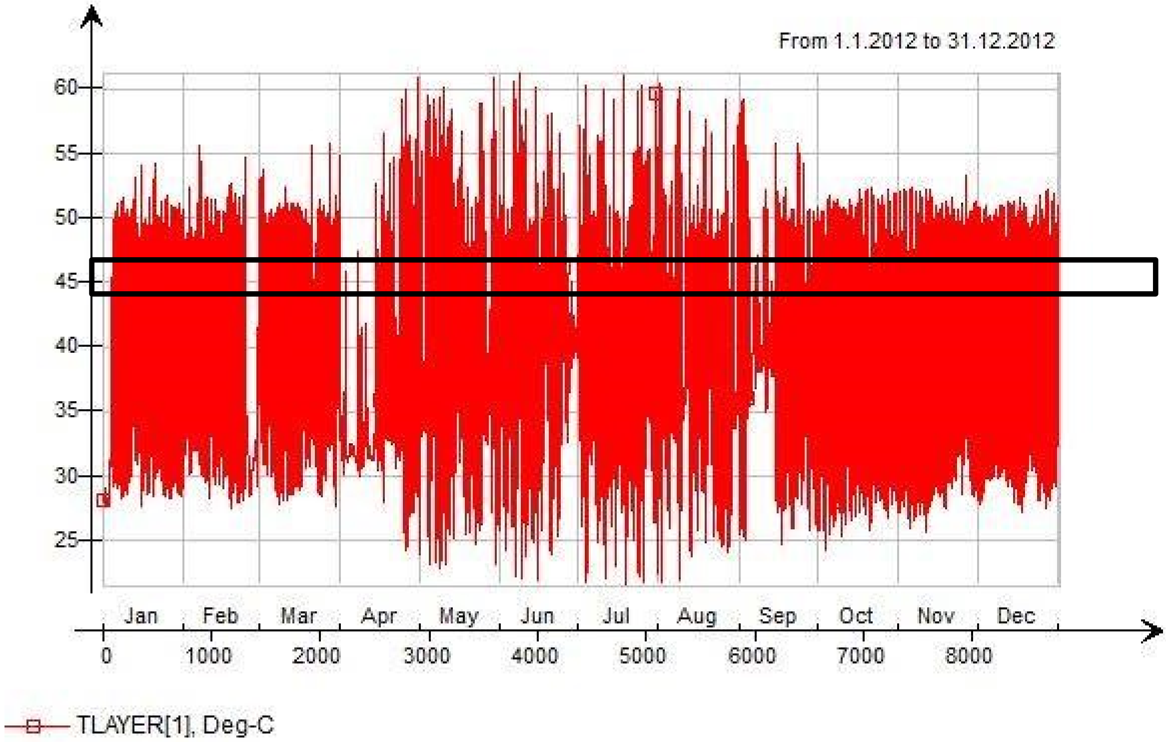


Figure 38. Temperature variation for 1st layer of hot storage tank

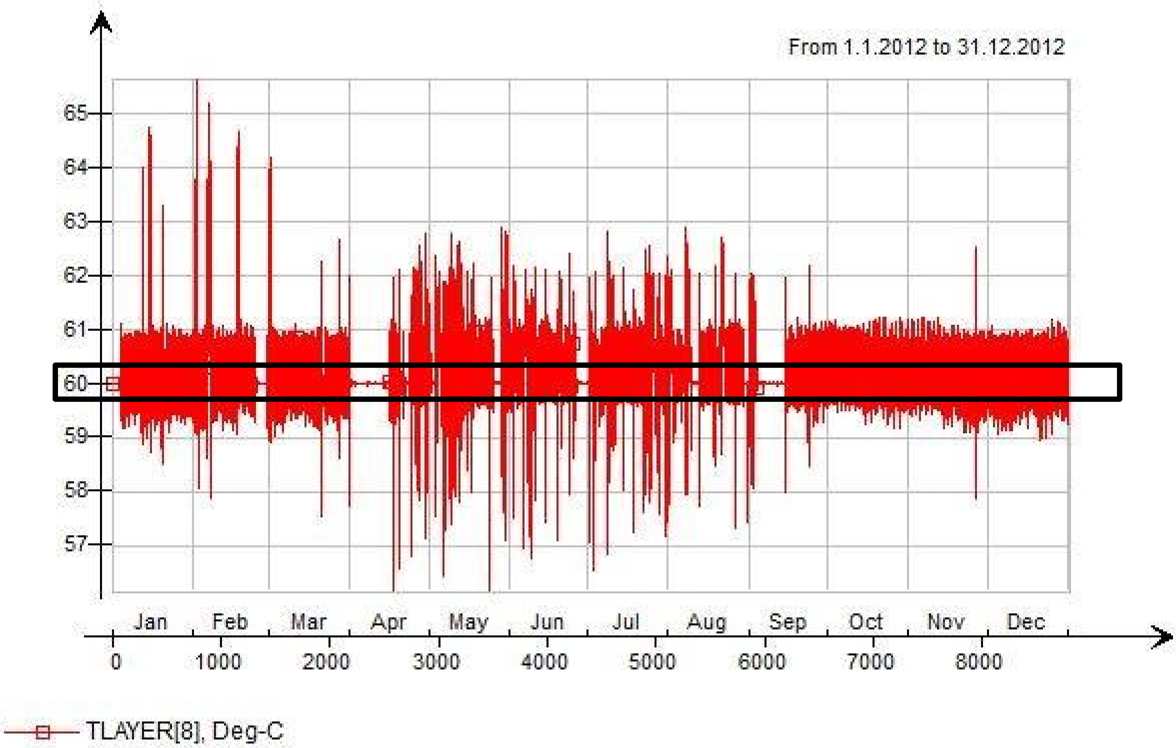


Figure 39. Temperature variation for 8th layer of hot storage tank

Figure 38 and 39 demonstrates temperature control happens when the low temperature tank reaches 45°C and the high temperature tank approaches to the 60°C. Space heating only with solar collector, space heating only without solar collector and domestic hot water only models show different states when low temperature and high temperature tank is applied.

7.1.1 The result of low temperature tank control strategy

Low-temperature tank links with the solar collector and AHU together for radiating building envelope and getting compensate energy from the solar collector. Air handling unit keeps the temperature of the room as 21°C constantly, thus the thermal comfort for occupants' behavior depends on heating load temperature satisfaction. To make the room temperature constant, supply air maintains the specific temperature value inside of AHU. Figure 40 shows how the supply air temperature is keeping stable when outdoor and return air to the AHU fluctuates by the year.

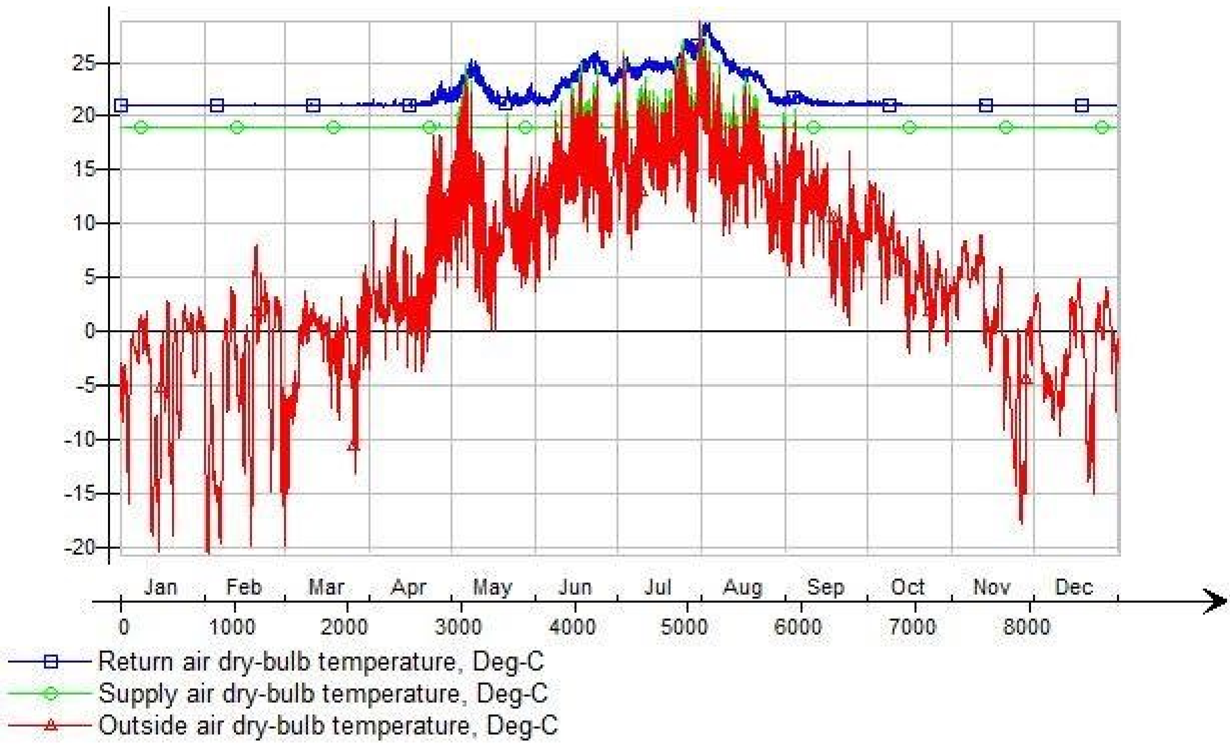


Figure 40. Temperature variation of return and supply air inside of AHU Depending on outdoor temperature

By the different outdoor temperature, inner building temperature should retain constant all the time thus radiators inside of room in the building maintains energy balance with the energy supplied to the AHU from the low temperature tank in the system model discussed earlier in figure 4. Usually Air handling unit installs on the concealed ceiling of the roof and for the whole zone of the building, AHU keeps the temperature constant controlling the air flow inside of the room.

Radiating the building inside works based on the solar collector operation connected to the low temperature tank, by the formulae (8). In detail, influence of solar thermal operation affects to the temperature variation of hot storage tank, ground heat exchanger and heat pump. Figure 41 and 42 demonstrates the temperature fluctuation in thermal tank model when the solar collector is equipped and not equipped case.

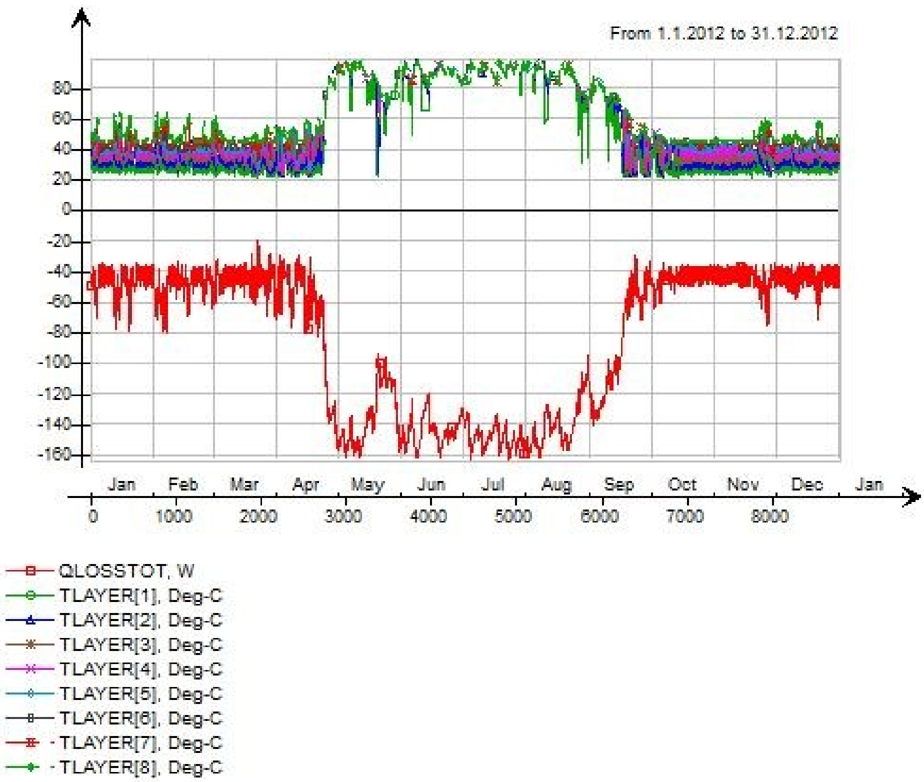


Figure 41. Temperature variation of hot storage tank
For space heating only light type building, tank size 1 m^3
With solar collector size, 7 m^2

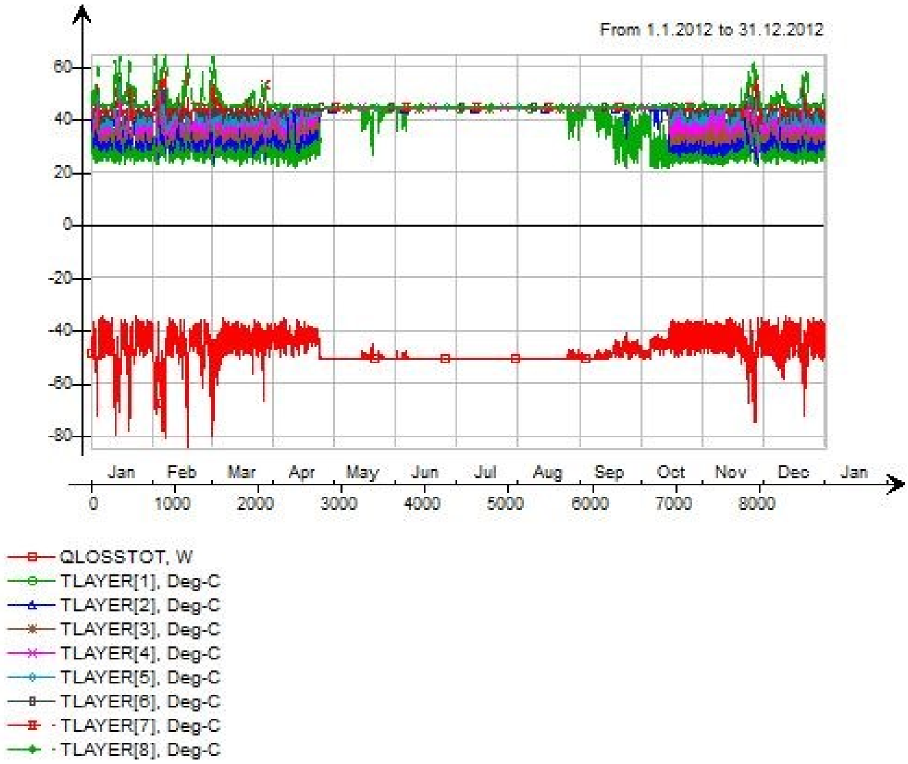


Figure 42. Temperature variation of hot storage tank
For space heating only light type building, tank size 1 m^3 without solar collector

Figure 41 and 42, both cases apply the hot tank, the size of $1m^3$. While the case of figure 41, solar collector size of $7m^2$ is equipped into the model and it does not use in the figure 42 model-case. For the optimization, 40 scenarios of building model are generated; for the tank, 0.5, 1, 1.5 and $2m^3$ size of tanks are employed and for solar collector, from 1 to 10 m^2 sizes with time step of 1 hour yearly data are used. In addition, massive, medium and light type building discussed earlier is studied, thus it generates all 120 building model samples in case of low-temperature control tank strategy.

Temperature of the thermal tank presents higher fluctuating temperature range when the solar collector installs because energy generation is possible in the solar tank not only from the heat pump model. This trend is more noticeable during the summer season in Finland.

Figure 43 and 44 is the mass flow, temperature variation and collected heat from the heat exchanger when the solar collector installed or not. Heat exchanger is direct connecting component with the heat pump in the ESBO plant; this result demonstrates the different result in the view of solar collector usage. It uses light type building for comparison and $1m^3$ size of tank with solar collector size of $7m^2$ employs into the model to discuss about the influence of the solar collector.

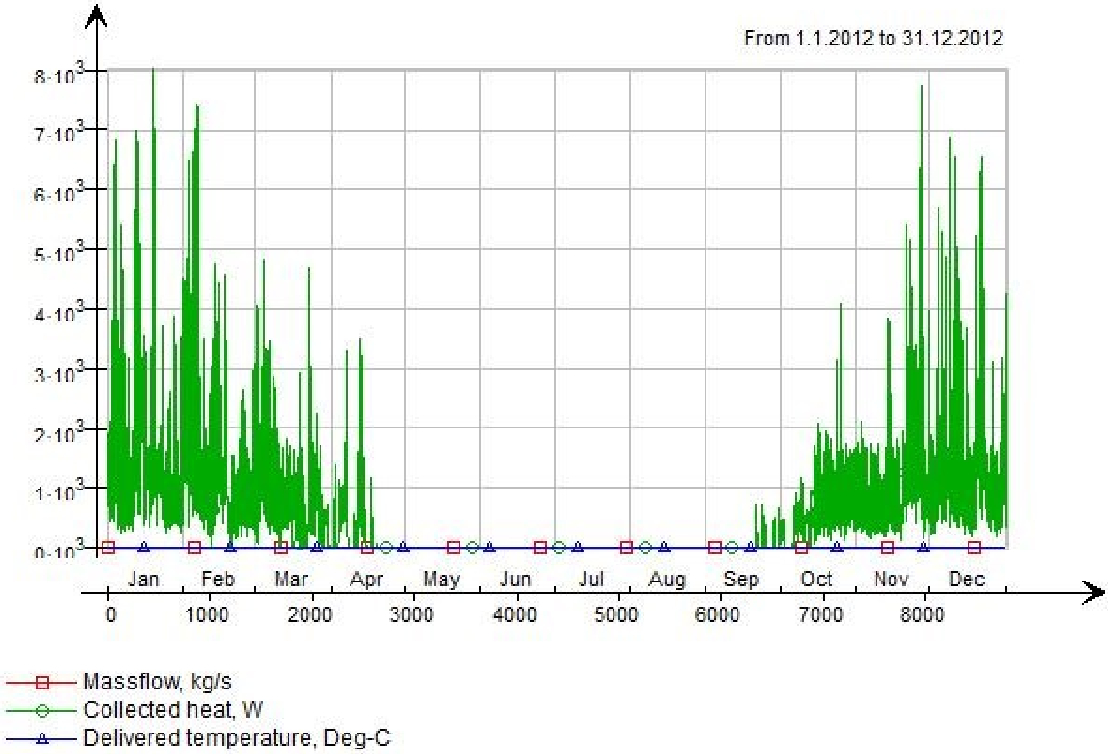


Figure 43. Collected heat, mass flow and temperature variation of ground heat exchanger for space heating only light type building, Tank size 1m^3 with solar collector size, 7m^2

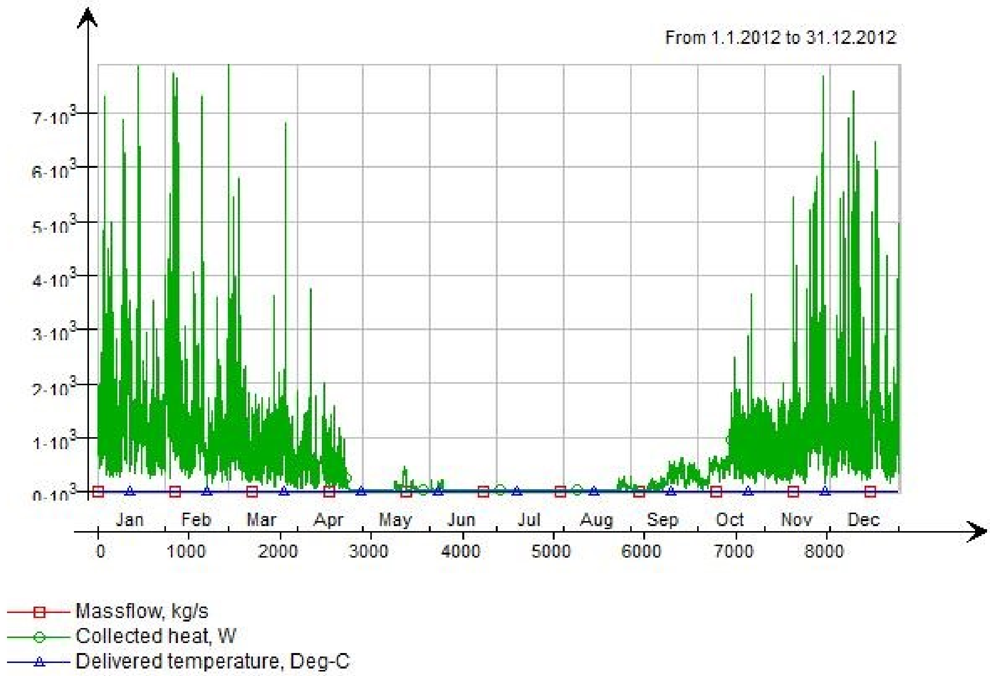


Figure 44. Collected heat, mass flow and temperature variation of ground heat exchanger for space heating only light type building, Tank size 1m^3 without solar collector

As it shows in the graph, tank connected to the solar collector gathers less heat from the heat exchanger, because solar collector works to make the tank temperature higher, heat exchanger connected to the heat pump generates less energy. This can check in the heat pump electricity consumption when the solar collector is on or off state.

Figure 45 and 46 shows how the electricity consumption fluctuates by the solar collector installation. This case also applies the light building with tank size of $1m^3$ and solar collector size of $7m^2$. When the solar collector is used, heat pump spends less energy and in the summer season, it becomes almost zero compared with heat pump model without solar collector.

When it comes to the Coefficient of Performance (COP), the effect of solar thermal is notable as figure 47 and figure 48 displays. It also demonstrates that in case of two storage tanks, solar collector better adopts to the low temperature tank for space heating than high temperature tank for domestic hot water usage. As it shows in one tank model, in the stratified tank, COP of the heat pump becomes higher with the solar collector because solar collector offers the heat transfer to the tank and occupies the lower temperature portion of the tank; heat pump only works for the high temperature layer of the tank.

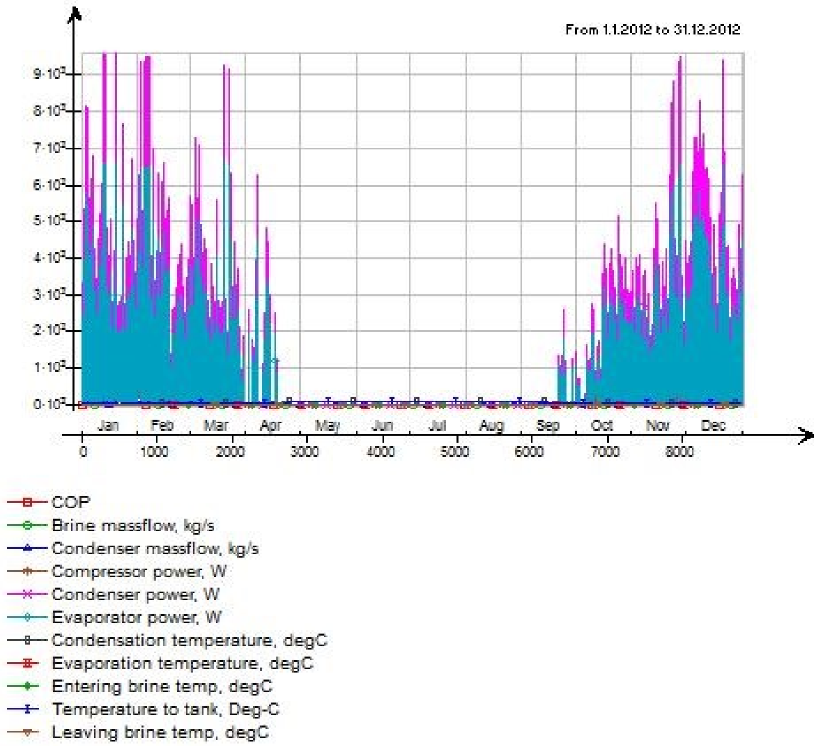


Figure 45. Heat pump electricity consumption
For space heating only light type building,
Tank size 1 m^3 solar collector size, 7 m^2

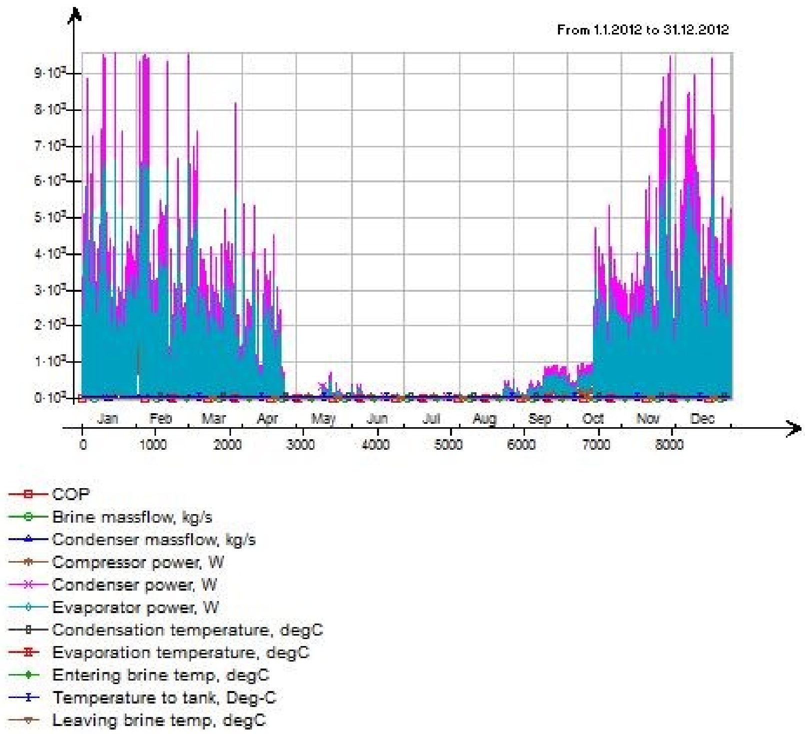


Figure 46. Heat pump electricity consumption
For space heating only light type building, tank size 1 m^3 without solar collector

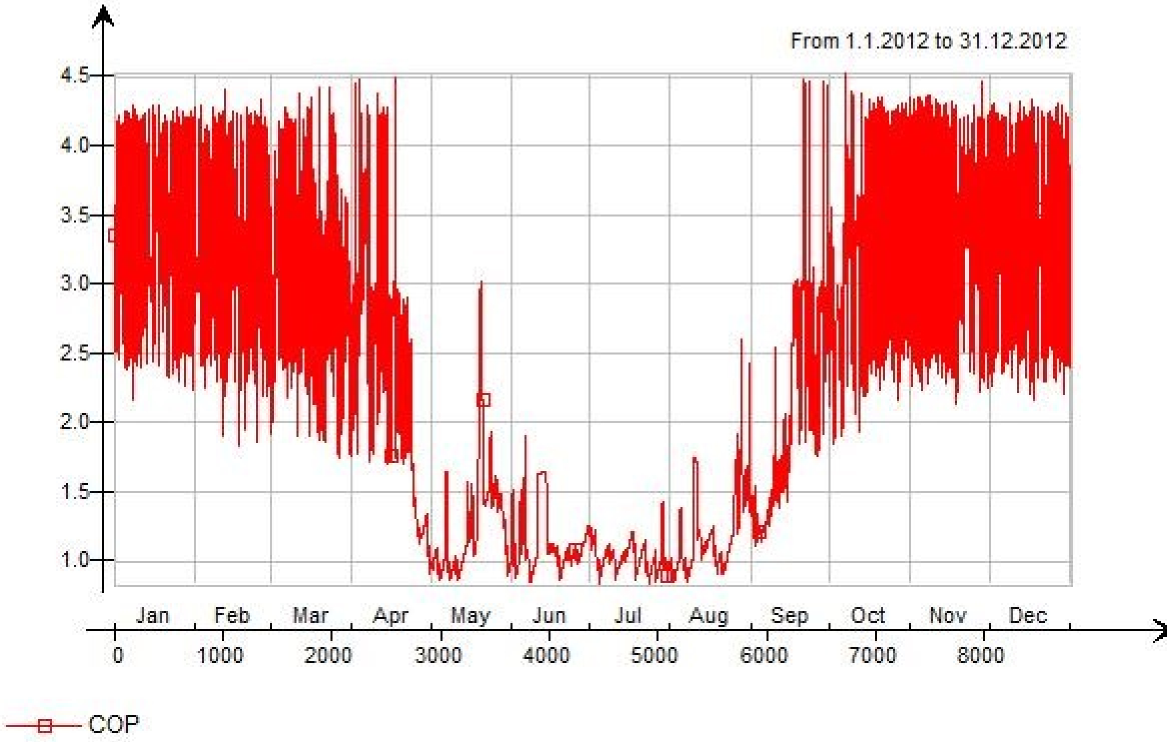


Figure 47. Coefficient of Performance (COP) variation of heat pump
For space heating only light type building, tank size 1 m^3
Solar collector size,7 m^2

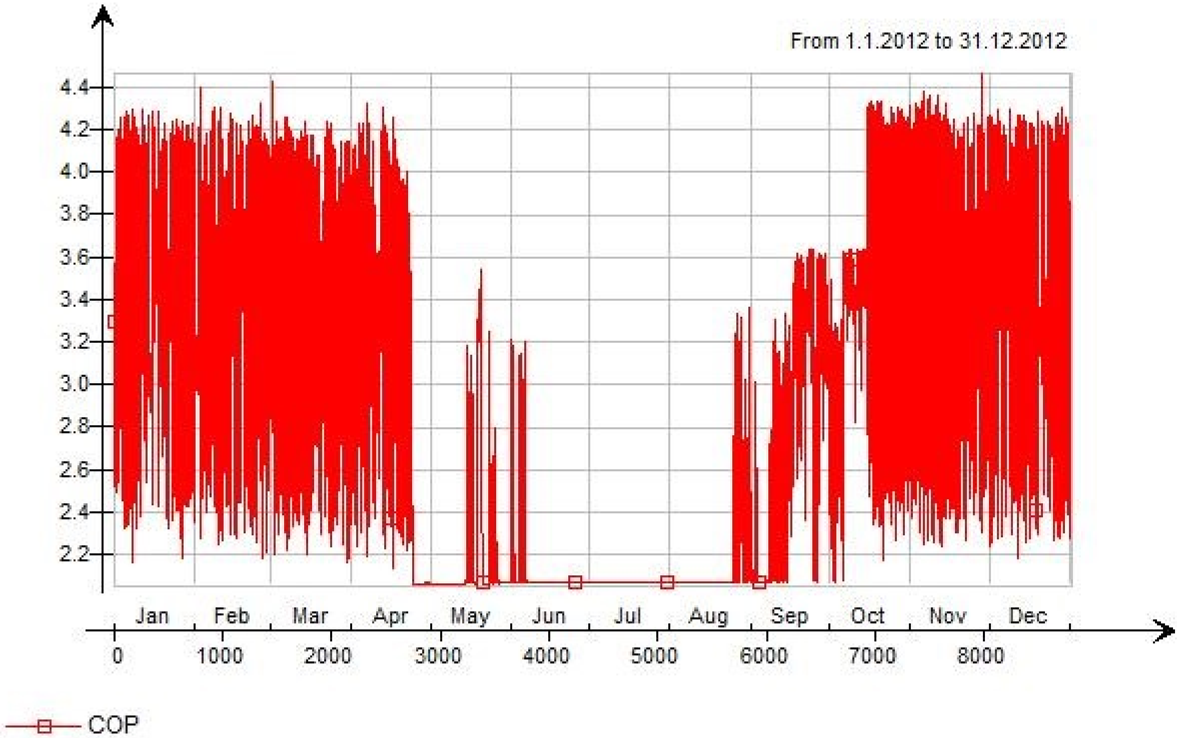


Figure 48. Coefficient of Performance (COP) variation of heat pump
For space heating only light type building, tank size 1 m^3 without solar collector

Solar collector effect can check more in the table 5 comparing with two energy utilization results.

kWh (sensible and latent)

Month	AHU heat recovery	AHU cold recovery	Plant heat recovery	Plant cold recovery	Solar heat	Ground heat	Ground cold	Ambient heat	Ambient cold
1	1099.0	0.0	-0.0	-1.9	3.0	990.7	0.0		
2	1029.0	0.0	-0.0	-1.7	42.7	869.7	0.0		
3	1054.0	0.0	-0.0	-1.6	158.0	560.2	0.0		
4	703.9	-0.0	-0.0	-1.3	264.8	161.4	-0.1		
5	417.2	-0.0	-0.0	-1.3	132.1	0.3	-0.8		
6	208.2	-0.0	-0.0	-1.2	105.6	0.1	-0.9		
7	100.2	-0.0	-0.0	-1.3	120.8	0.1	-1.0		
8	170.6	-0.0	-0.0	-1.3	107.8	0.2	-0.9		
9	409.5	-0.0	-0.0	-1.5	168.7	19.6	-0.3		
10	665.3	0.0	-0.0	-1.9	39.4	443.4	0.0		
11	887.4	0.0	-0.0	-1.8	6.2	756.7	0.0		
12	1057.0	0.0	-0.0	-1.9	2.5	884.5	0.0		
Total	7801.3	-0.0	-0.0	-18.6	1151.7	4686.8	-4.2		

kWh (sensible and latent)

Month	AHU heat recovery	AHU cold recovery	Plant heat recovery	Plant cold recovery	Solar heat	Ground heat	Ground cold	Ambient heat	Ambient cold
1	1099.0	0.0	-0.0	-1.9		992.2	0.0		
2	1029.0	0.0	-0.0	-1.7		905.6	0.0		
3	1054.0	0.0	-0.0	-1.7		656.5	0.0		
4	703.9	-0.0	-0.0	-1.3		304.9	0.0		
5	417.2	-0.0	-0.0	-1.3		42.2	0.0		
6	208.2	-0.0	-0.0	-1.3		26.2	0.0		
7	100.2	-0.0	-0.0	-1.3		18.6	0.0		
8	170.6	-0.0	-0.0	-1.4		33.2	0.0		
9	409.5	-0.0	-0.0	-1.4		139.9	0.0		
10	665.3	0.0	-0.0	-1.9		466.9	0.0		
11	887.4	0.0	-0.0	-1.8		762.0	0.0		
12	1057.0	0.0	-0.0	-1.8		886.0	0.0		
Total	7801.3	-0.0	-0.0	-18.8		5234.1	0.0		

Table 6. Utilized energy from the system for space heating only model
In the light type building,
Tank size 1m^3 with 7m^{2}solar collector / without solar collector

Higher COP, more heat collected and less energy usage in the space heating with solar collector model studies that control strategy in the low temperature tank is dependent on the simulation result of solar collector operation and low temperature inner state in the energy balance side. Space heating only models generate 132 samples in this case, result shall adopt in control and optimization combining domestic hot water only tank model.

7.1.2 The result of high temperature tank control strategy

High temperature tank control follows domestic hot water only tank case. From the standard IDA one tank model, it deletes the function of AHU and solar collector. It only tags along the domestic hot water usage profile from occupants by the tank size; temperature fluctuation inside of thermal tank decides in figure 49. Compared with previous case with solar collector, graph shows stable aspect even in stratified status of tank.

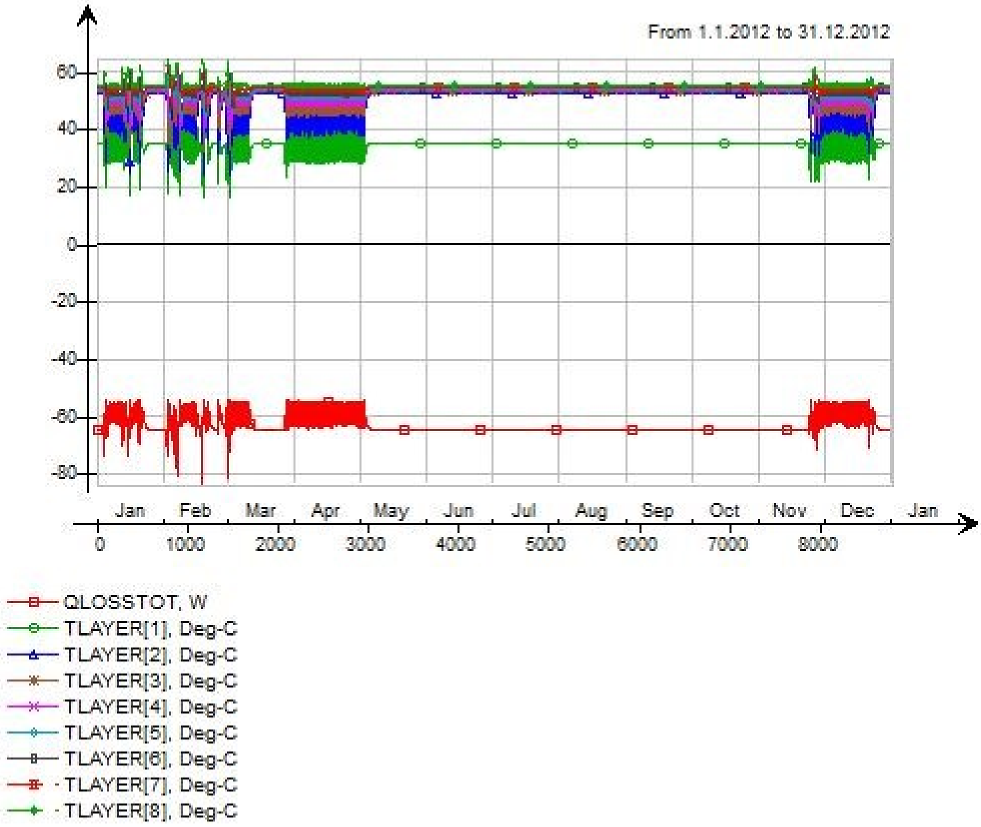


Figure 49. Temperature variation of hot storage tank for Domestic hot water only light type building, tank size 1m^2

COP of the heat pump connected to the domestic hot water only tank shows better steady condition than low temperature tank case with solar collector. This only attaches to the regular profile data from input water consumption schedule and tank size.

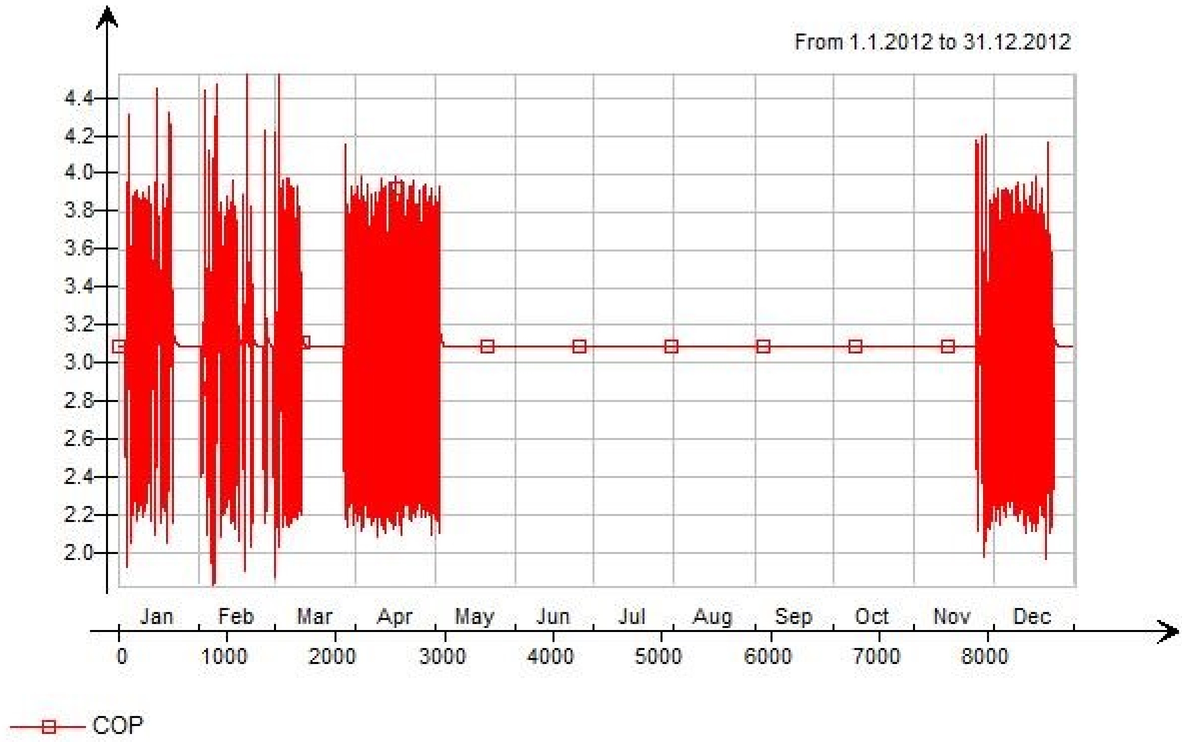


Figure 50. Coefficient of Performance (COP) variation of heat pump For domestic hot water only light type building, tank size 1 m²

Result for the utilized energy has no data about AHU heat recovery, only presents energy generation for the ground source heat pump.

Utilized free energy

kWh (sensible and latent)

Month	AHU heat recovery	AHU cold recovery	Plant heat recovery	Plant cold recovery	Solar heat	Ground heat	Ground cold	Ambient heat	Ambient cold
1			-0.0	-1.7		404.9	0.0		
2			-0.0	-1.7		376.6	0.0		
3			-0.0	-1.8		404.4	0.0		
4			-0.0	-1.7		395.2	0.0		
5			-0.0	-1.3		403.8	0.0		
6			0.0	-1.4		386.8	0.0		
7			0.0	-1.5		399.7	0.0		
8			0.0	-1.5		399.7	0.0		
9			0.0	-1.4		386.8	0.0		
10			0.0	-1.5		399.7	0.0		
11			-0.0	-1.8		386.0	0.0		
12			-0.0	-1.5		408.6	0.0		
Total			-0.0	-18.7		4752.2	0.0		

Table 7. Utilized energy from the system for domestic hot water only model In the light type building, tank size 1m²

For combining the result and producing optimization, 4 each domestic hot water only case ($0.5m^3$, $1m^3$, $1.5m^3$, $2m^3$) in the light weight, medium and massive passive type of building is considered. 12 amounts of samples for three-insulation type of buildings can generate.

7.1.3 The result of solar collector control strategy

Solar collector balances up the energy generation of the heat pump as it discussed previous. Hence, solar collector and low temperature tank control demonstrates directly how the heat collected from the solar collector works for compensating the energy utilization of the heat pump. Figure 51 is the heat collected from the solar collector in the light building type when the size of solar collector is $7m^2$. This result can compare with low temperature tank collected heat and temperature variation discussed in previous chapter.

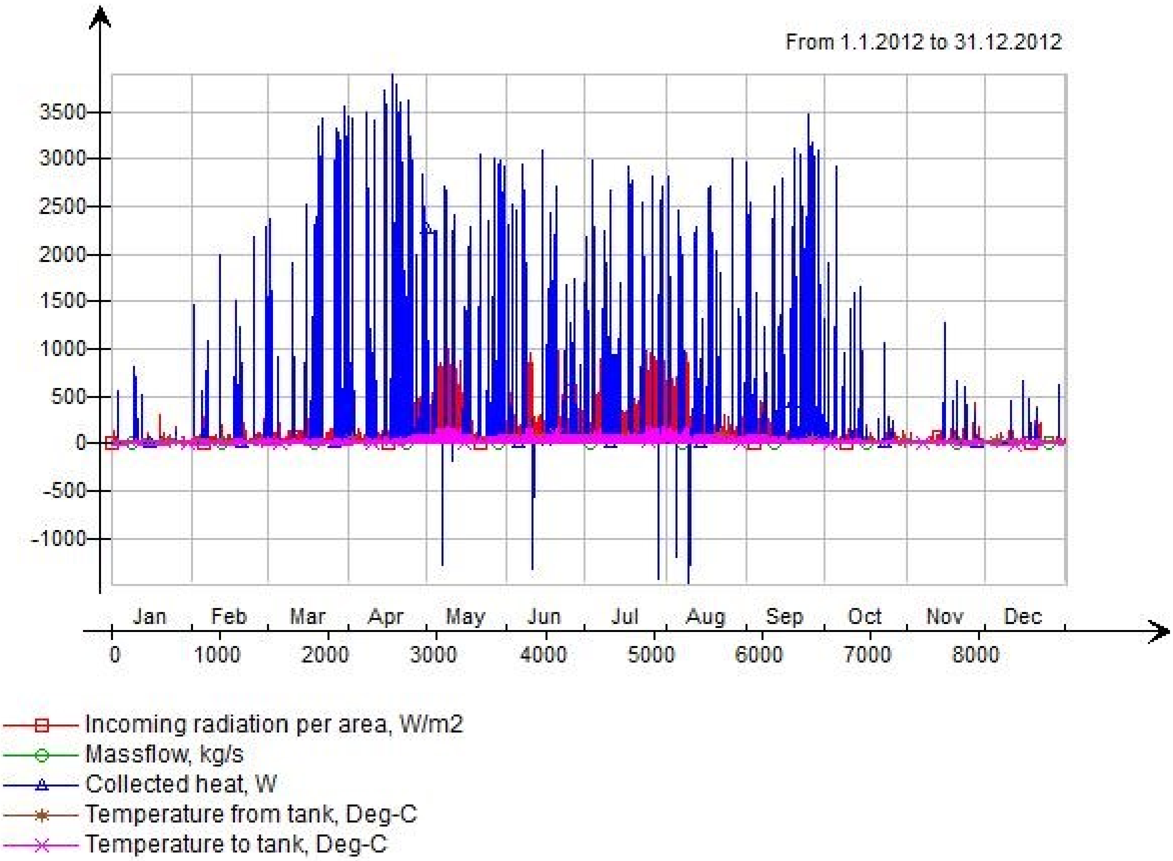


Figure 51. Heat collected from the solar thermal for Space heating only light type building, Tank size 1 m^3 with solar collector size, 7 m^2

Heat collected from the solar collector employs into the low temperature tank directly, and it showed as figure 28 before. To check the heat collected, same size of 7 m^2 solar thermal and tank size 1 m^3 is installed. As two figures(Figure 43, 44) explain, collected heat from the solar thermal makes the heat pump operation less and generates less electricity. When it sees the COP of the heat pump, this is dependent on the temperature variation from the solar collector to the tank.

Temperature of the space-heating tank keeps it as 45°C, thus when the temperature approaches around 40°C from the tank to the solar thermal, then the valve for liquid mass flow opens and the flat plate type solar panel receives energy from the thermal tank. After absorbing the solar energy, the valve between the solar panel and the low temperature tank opens and sends back the liquid from the solar thermal to the tank when the temperature of liquid reaches approximately 50°C, the energy balance of the low temperature tank finalizes with solar thermal.

Figure 52 and 53 is the temperature water in the tank from the tank and to the tank when the solar collector size is 7m^2. As it displays, inlet temperature to the tank becomes higher than the temperature from the tank receiving the solar energy showing the effect of solar panel. Size of the solar panel affects to the temperature of low-temperature tank and this shall discuss in the optimization for the suitable selection of the solar collector by the different building type.

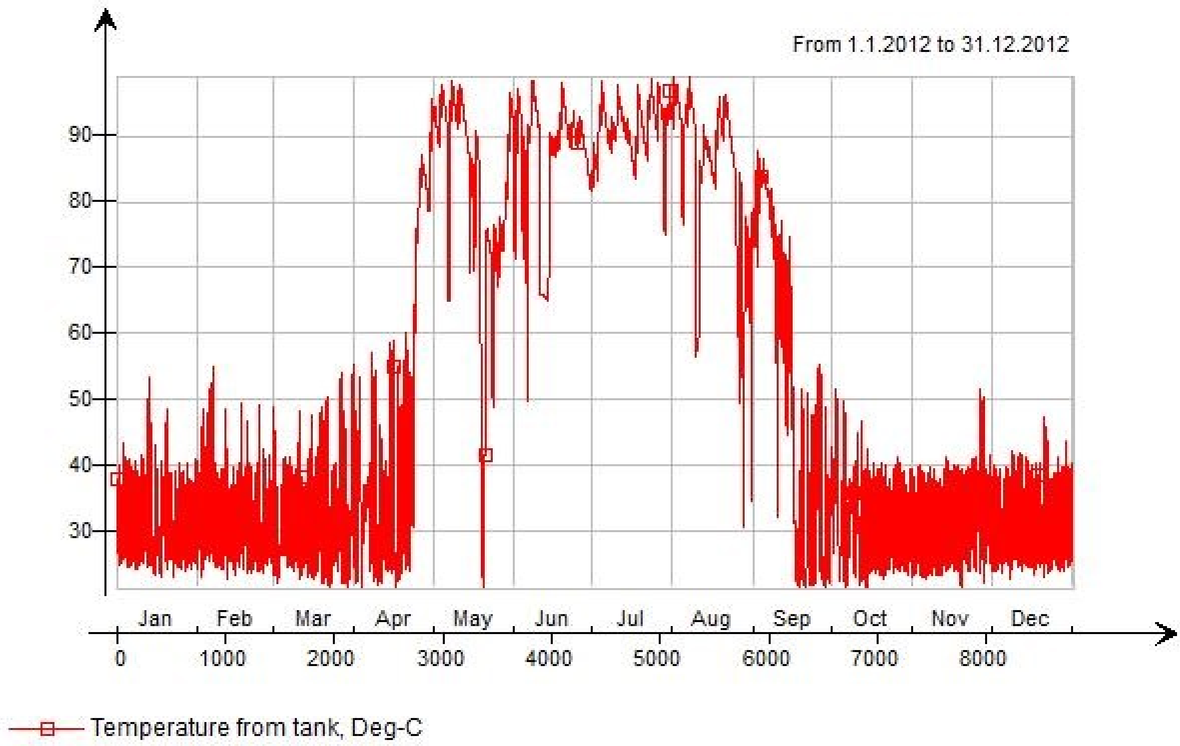


Figure 52. Temperature water in the tank from the tank During solar collector size, 7 m^2

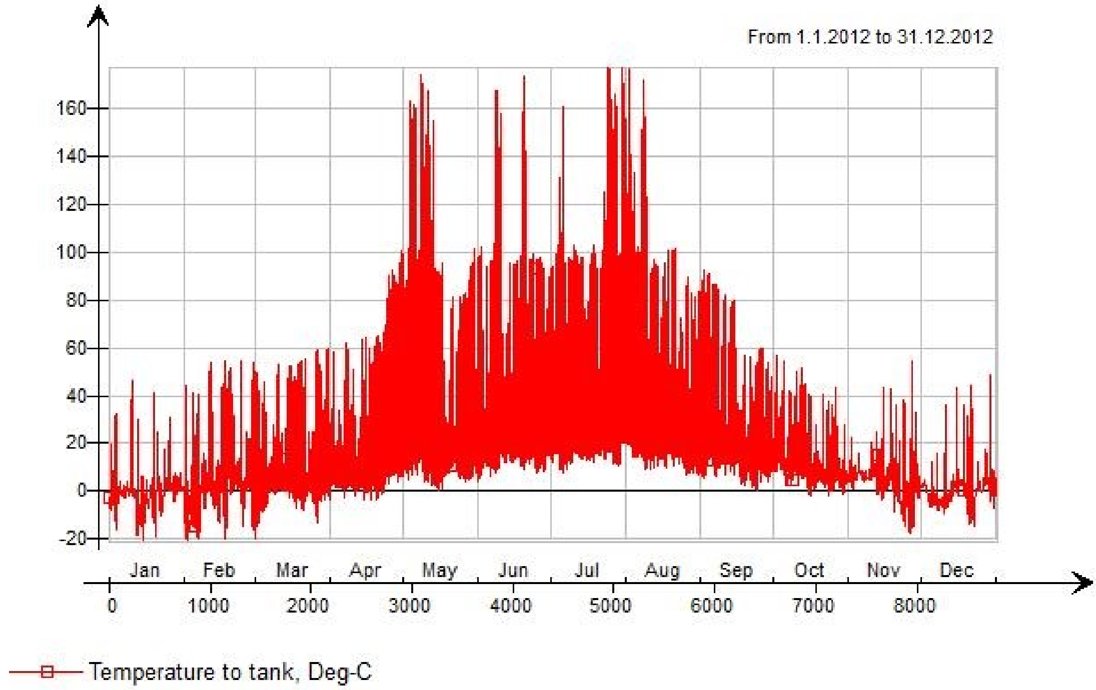


Figure 53. Temperature water in the tank to the tank During solar collector size, 7 m²

7.2 Artificial neural network result

The results from the ANN shows error histogram and regression plot from figure 54 to figure 65 as heat pump and solar collector energy generation by the type of building envelope. Figure 54 and 55 is the error histogram and regression plot result for the neural network in the lightweight building when the input vector decides as ground source heat pump energy generated. In the figure 54, blue bars represent training data, the green bars show validation data, and the red bars are testing data while the ideal zero error, so called mean square error (MSE) is orange line. Histogram signifies the outliers, which are apart from the major dataset, here shows as -95.57 in training when most cases fall between -17.3 to 28.36. Checking the outlier data is good way to monitor the whole dataset if the outlier data is valid point. If outliers are valid but unlike the rest of dataset as Figure 54, network is extrapolating for these points. Another method is making more hidden neurons and training trials repeatedly. In this plot, hidden neuron layer of 10 is used.

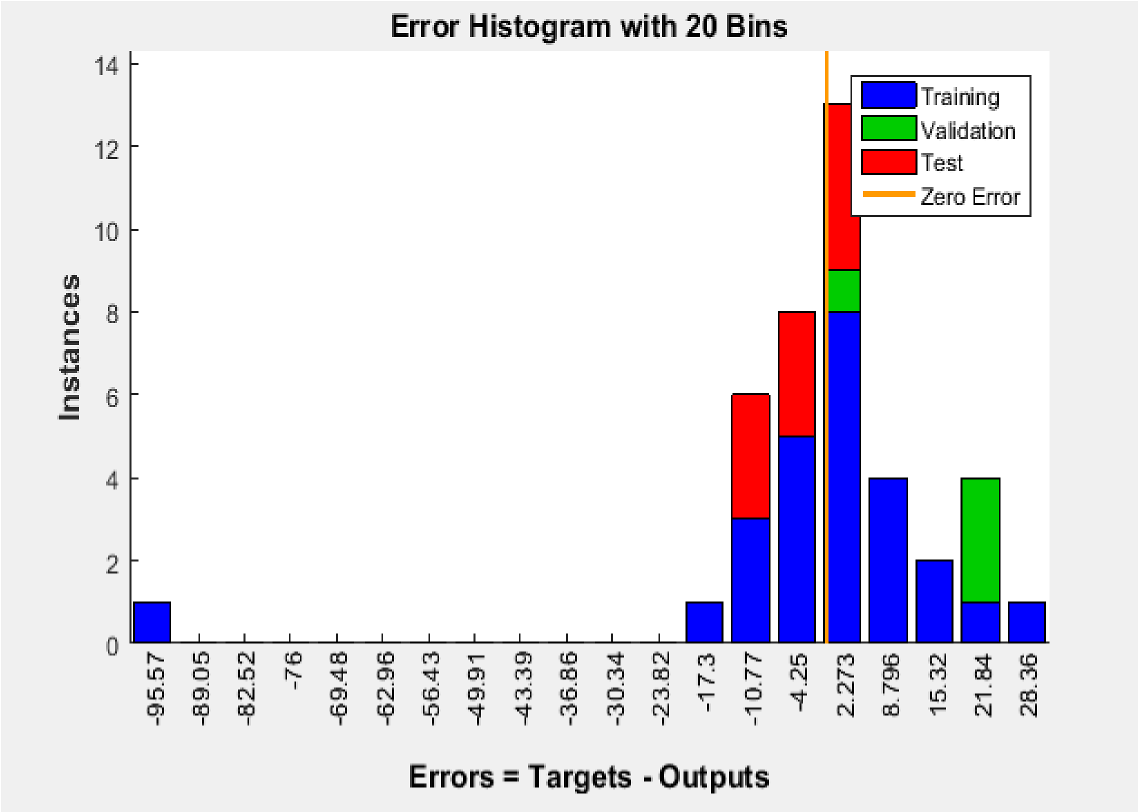


Figure 54. Error histogram for neural network in the lightweight building (GSHP)

In the figure 55, regression plot displays with training, validation and test sets. X-axis is the target objectives and the Y-axis represents the output layer with the weight and bias values. For the ideal fit, the data should fall along the 45-degree line as different colored; however, this plot shows reasonably good with R-value in each case of 0.93 or the above. For more accurate dataset, training the network repeatedly recommends.

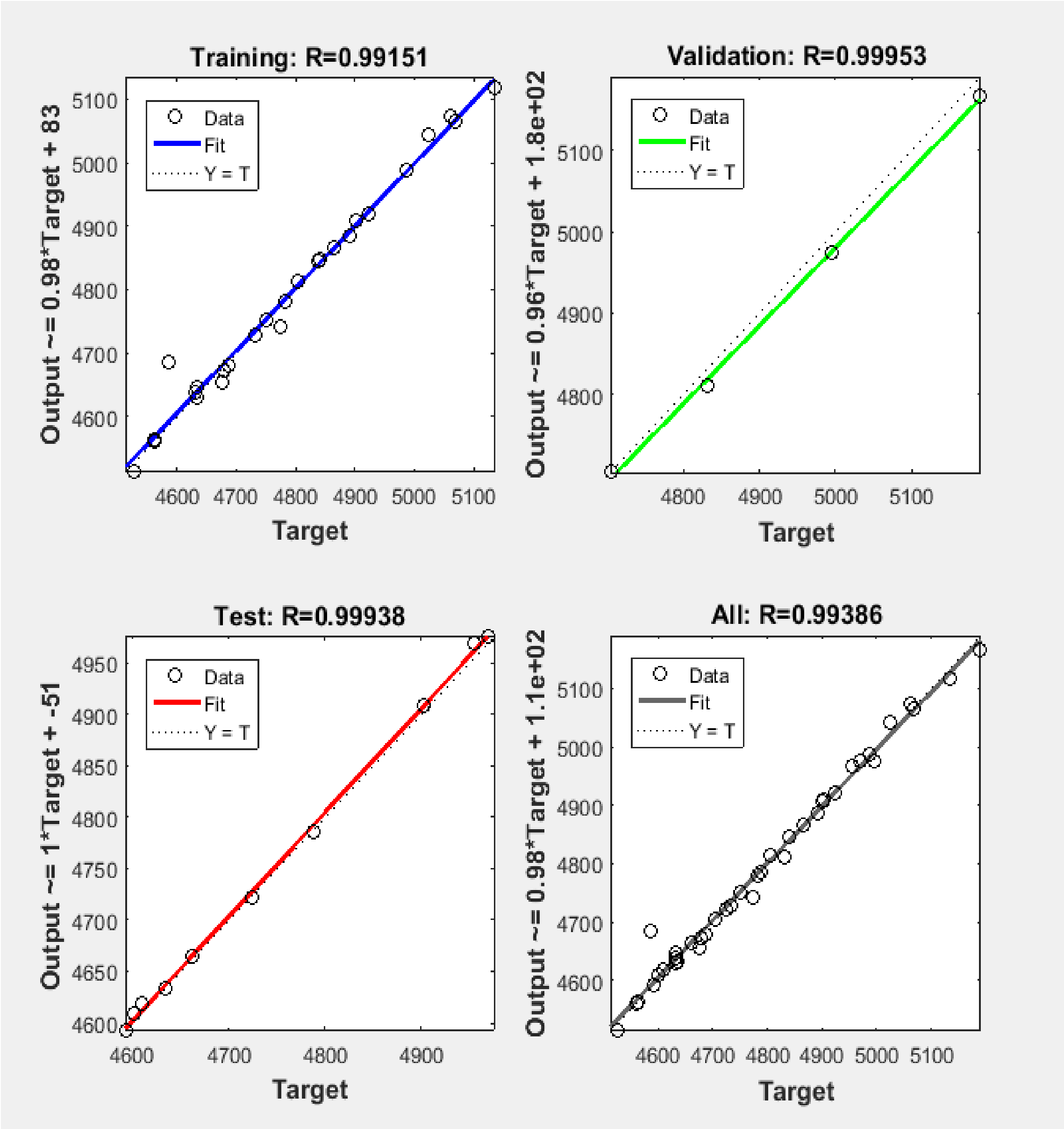


Figure 55. Regression plot for neural network in the lightweight building (GSHP)

Solar collector heat generated vector also checks after making Artificial Neural Network. Figure 56 and 57 is the error histogram and regression plot result for the neural network in the lightweight building when the input vector decides as solar thermal collector energy generated. As discussed previous, histogram outlines the boundary for the training, validation and test dataset compared with the zero error line (Mean Square Error). Regression plot also falls near to the ideal 45° slope from the ground line.

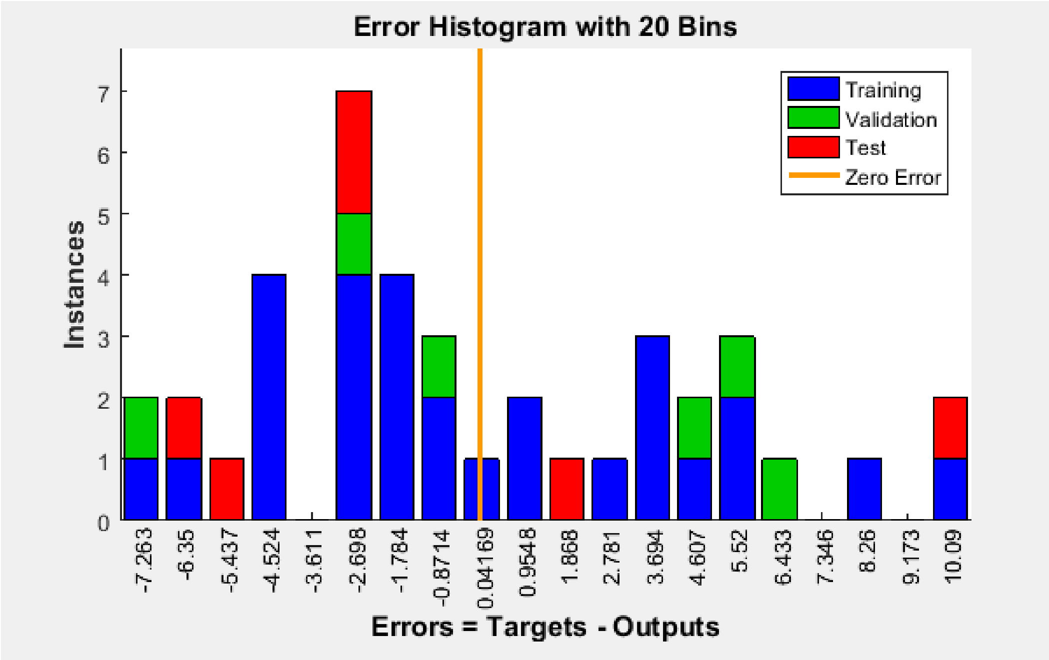


Figure 56. Error histogram for neural network in the lightweight building (Solar thermal)

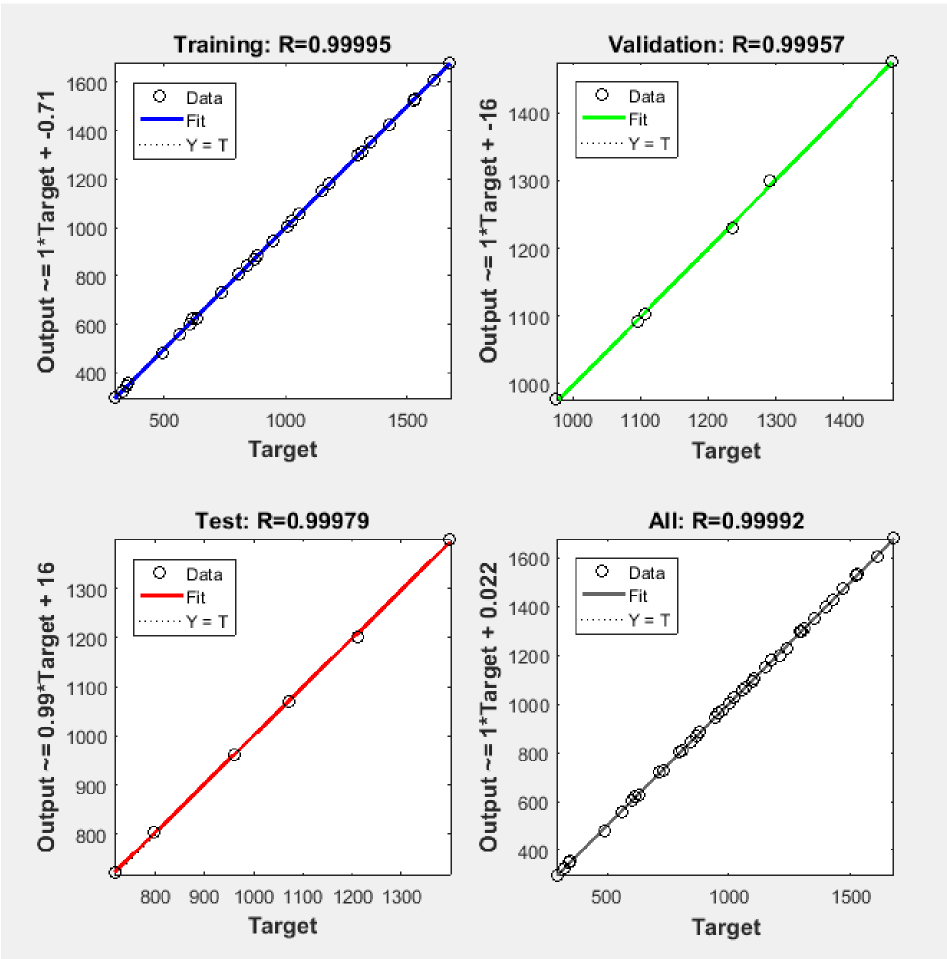


Figure 57. Regression plot for neural network in the lightweight building (Solar thermal)

Figure 58 and 59 is the error histogram and regression plot result for the neural network in the medium weight building when the input vector decides as ground source heat pump energy generated.

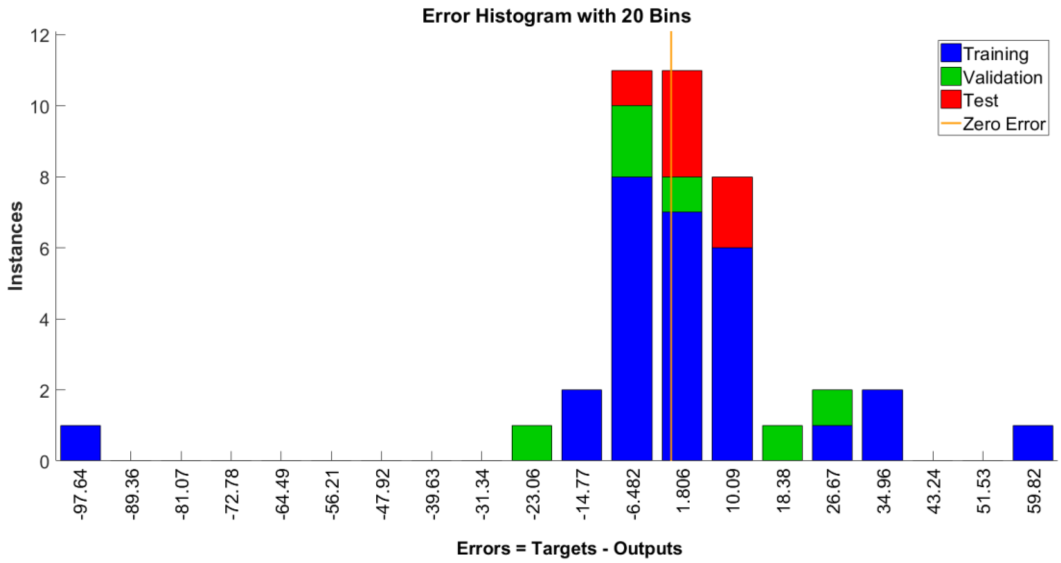


Figure 58. Error histogram for neural network in the medium weight building (GSHP)

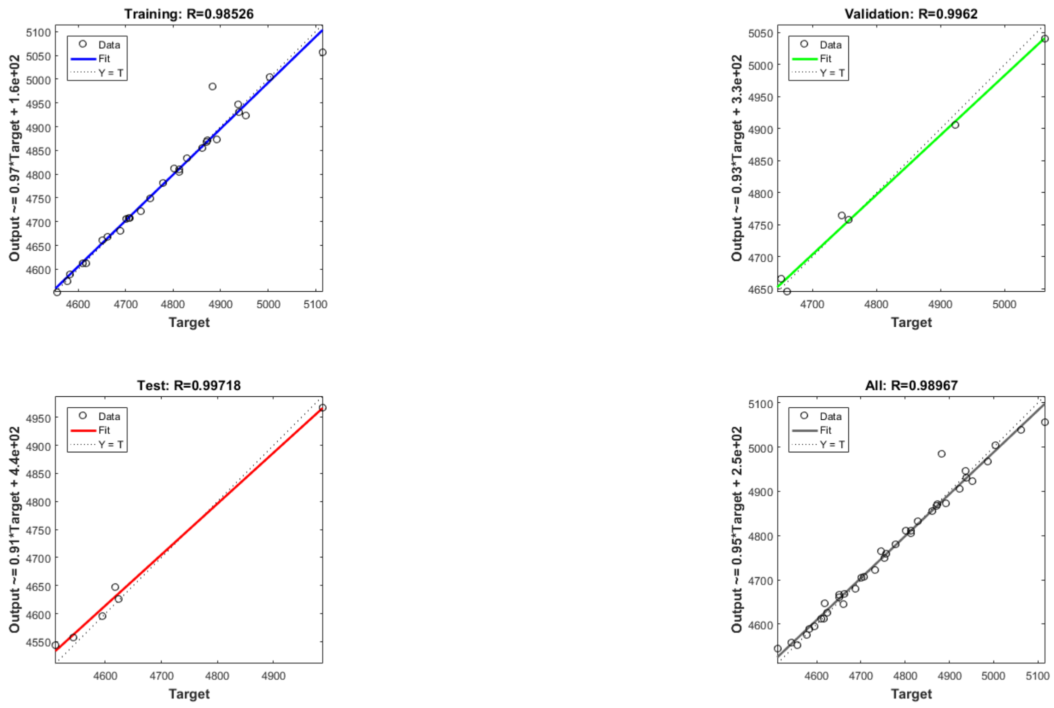


Figure 59. Regression plot for neural network in the medium weight building (GSHP)

Figure 60 and 61 is the error histogram and regression plot result for the neural network in the medium weight building when the input vector decides as solar thermal collector energy generated.

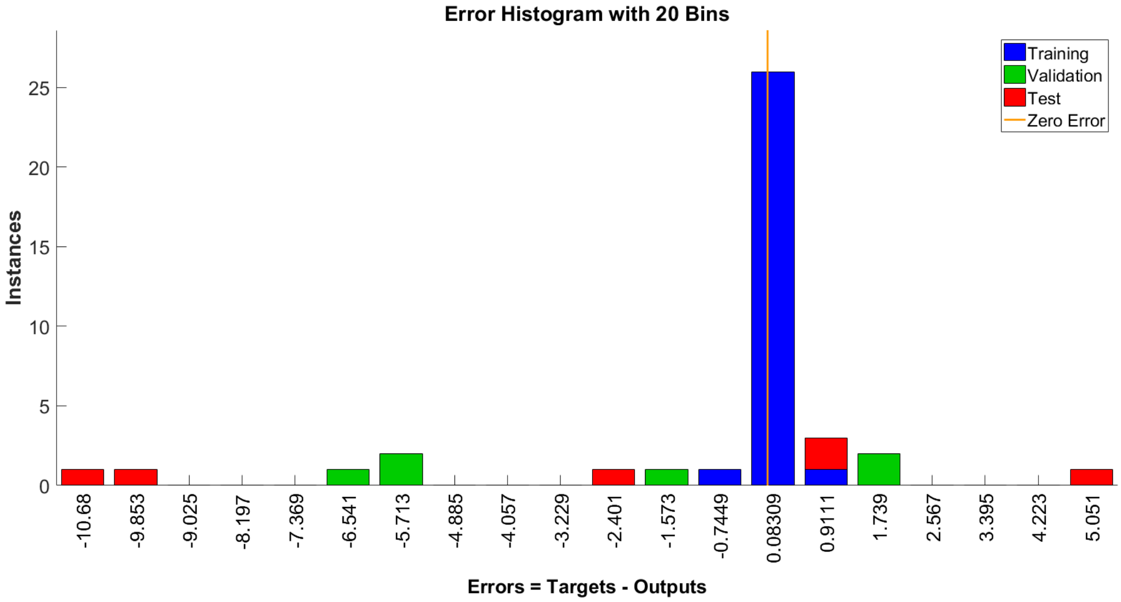


Figure 60. Error histogram for neural network in the medium weight building

(Solar thermal)

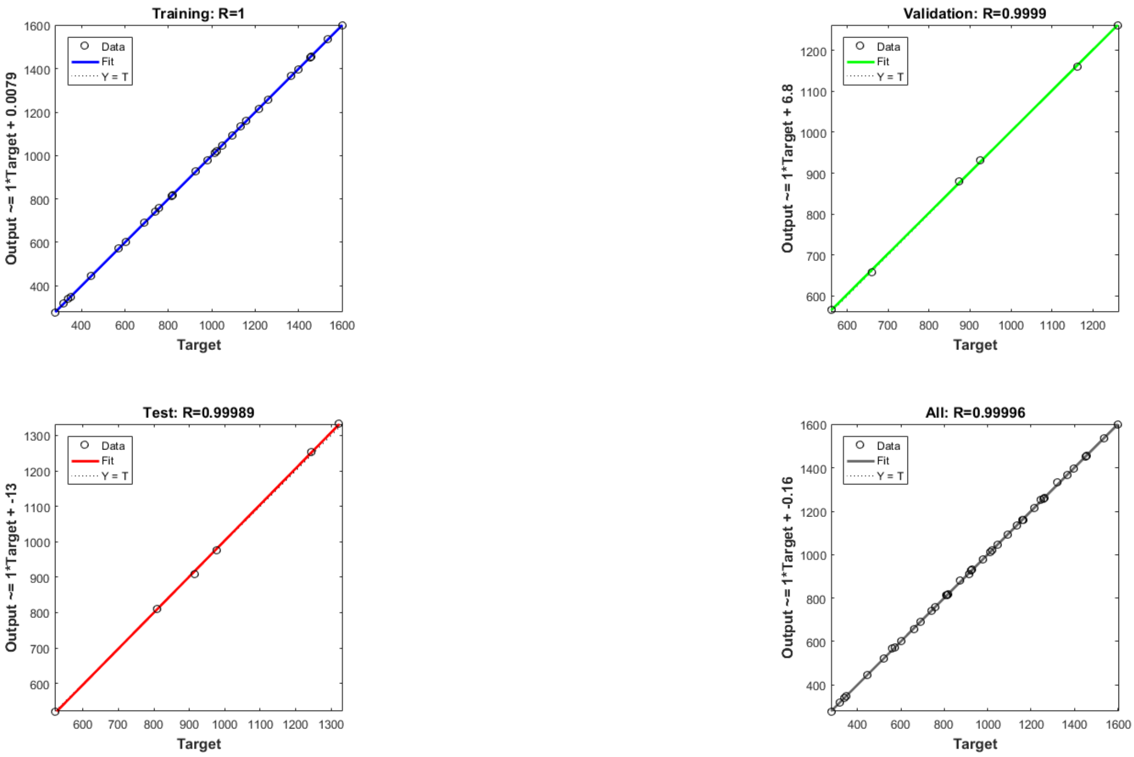


Figure 61. Regression plot for neural network in the medium weight building

(Solar thermal)

Figure 62 and 63 is the error histogram and regression plot result for the neural network in the massive weight building when the input vector decides as ground source heat pump energy generated.

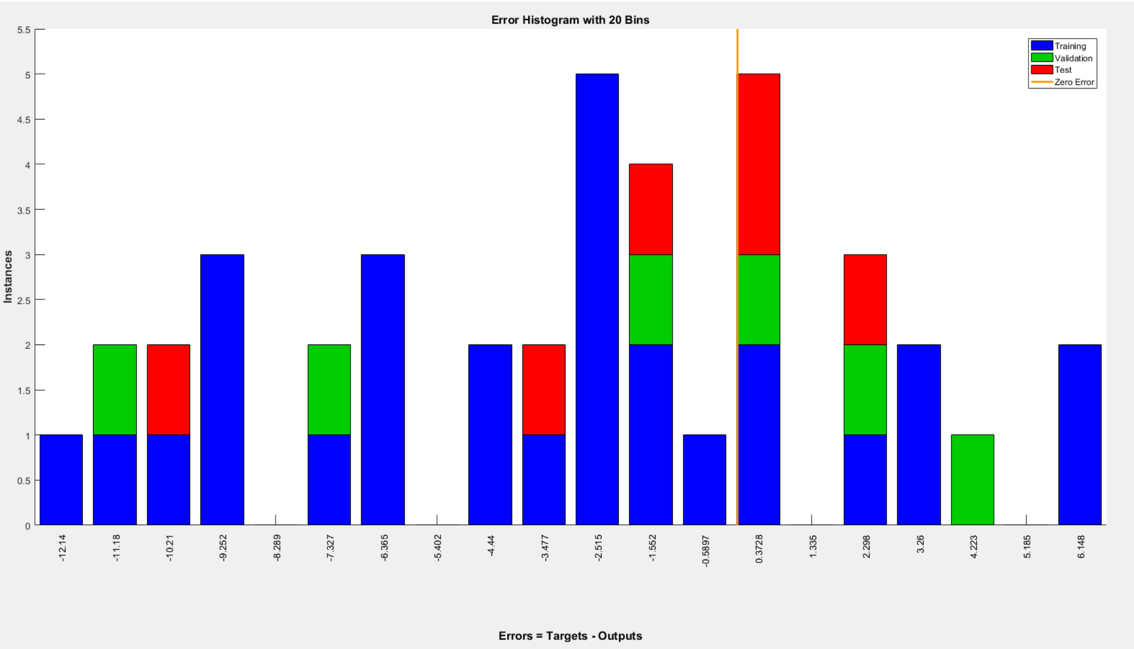


Figure 62. Error histogram for neural network in the massive weight building (GSHP)

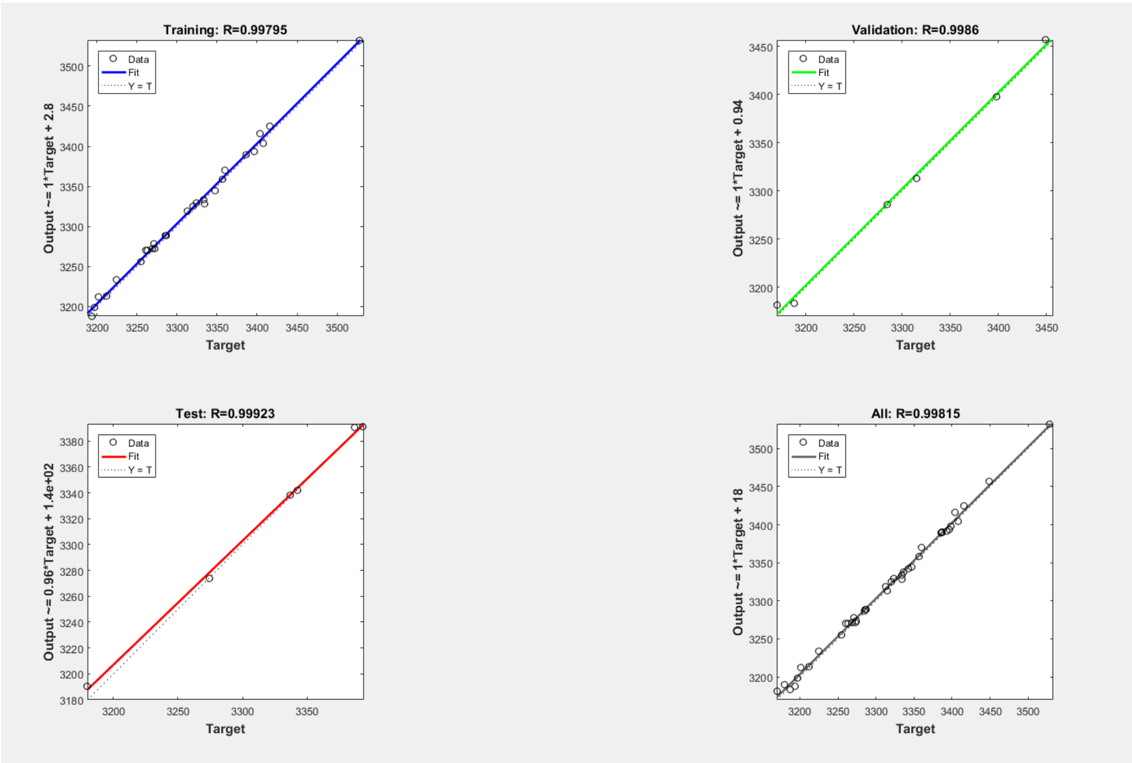


Figure 63. Regression plot for neural network in the massive weight building (GSHP)

Figure 64 and 65 is the error histogram and regression plot result for the neural network in the massive weight building when the input vector decides as solar thermal collector energy generated.

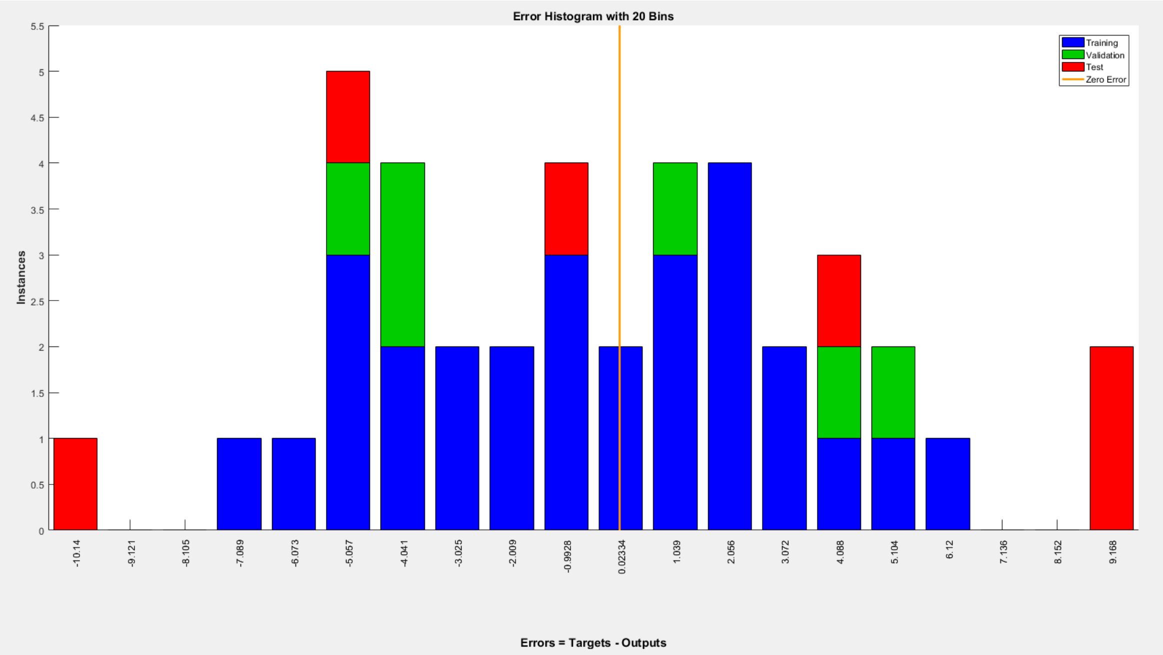


Figure 64. Error histogram for neural network in the massive weight building

(Solar thermal)

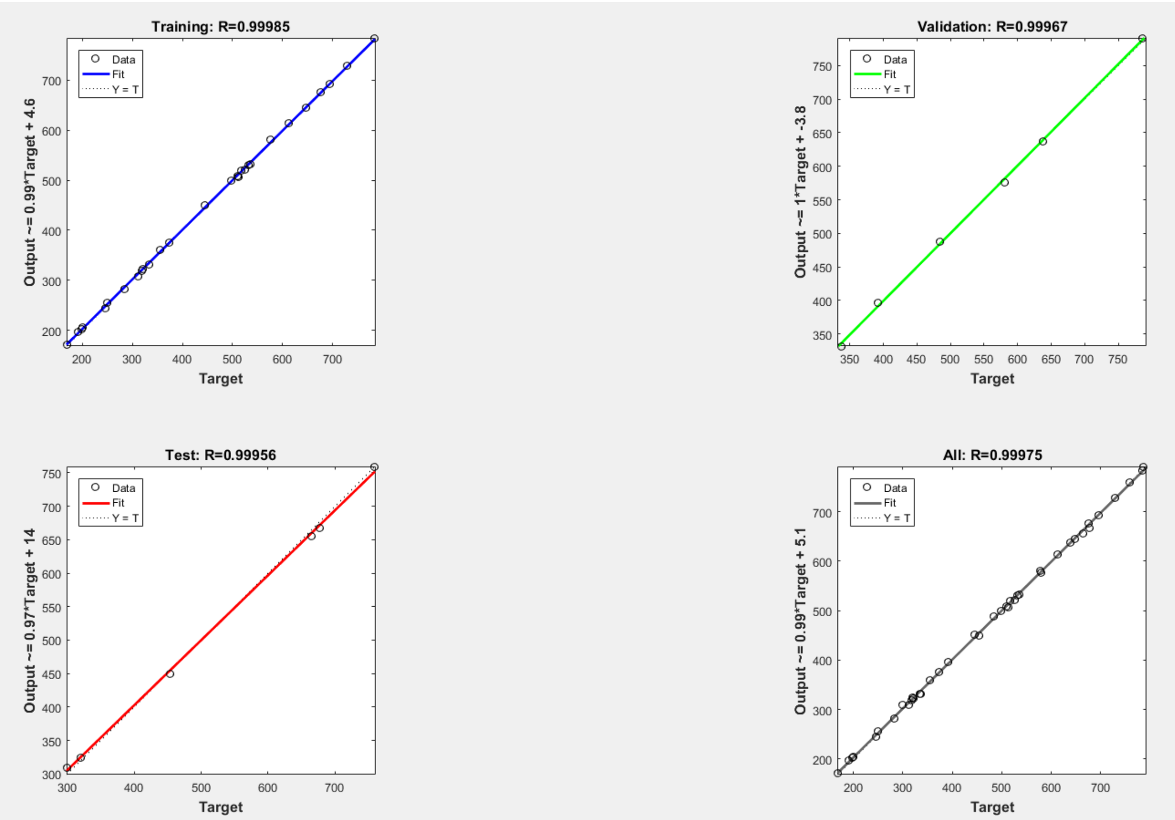


Figure 65. Regression plot for neural network in the massive weight building

(Solar thermal)

The selected networks have the simpler structure and at the same time the best performance. The simple structure is important, since the higher number of hidden layers and neurons lead the model to over fitting. In over fitting because of high number of hidden layer and corresponding neurons, the model estimates the reference data, which are available in training set. Nevertheless, the model is not able to estimate those cases out of training data set. To make the above graph of error histogram and regression plot satisfying the reasonable result in the view of performance and avoiding overfitting, histogram result is checked to make bars enter similar to the mean square error line, while regression plot R value falls less behind 0.93 value. ANN result from the solar collector input layer shows less error than when it comes to the input layer signifies as the heat pump, general target output of solar collector energy generation is less than the heat pump electricity consumption. Compared with the light and medium type of building, massive building shows less error because building shape is passive type good for insulation and better for storing the energy thus less energy generation is required from the target input layer fulfilling the zero-energy building case.

7.3 Multi Objective optimization result

7.3.1 Cost of energy components

The price for components shows as values in table 8. This information is a part of wide price data set gathered by HVAC technology research group. For the electricity, the price considers as 11 (c/kWh) which includes those factors in Table 8.

Finish VAT	Electricity tax (c/kWh)	Company margin (c/kWh)	Distribution cost (c/kWh)	Feed-in tariff (c/kWh)
24%	2.79372	0.3	3.98	8.35

Table 8. Electricity price based on information of 2012

For thermal solar panel the unit price is 609 (€/m^2). This price is average of available information from HP4NZEB in Aalto price data. The information in HP4NZEB estimates based on real projects. For the tank, the price extracts according to information of AKVATERM Company for thermal tank type series as Table 9 demonstrates.

Height (m)	Diameter (m)	Volume (m3)	Price (€)	Unit price (€/m3)
2.050	0.650	0.68	1819.00	2675.36
2.050	0.800	1.03	2199.00	2135.12
2.050	0.950	1.45	2305.00	1587.09
2.100	1.050	1.82	2579.00	1419.00
2.150	1.250	2.64	3285.00	1245.68
2.250	1.400	3.46	3649.00	1054.06
2.250	1.500	3.97	3339.00	840.20
2.300	1.600	4.62	3539.00	765.67
2.350	1.800	5.98	4799.00	802.91

Table 9. Price of the hot water storage tank

In the end the LCC can present as

$$LCC_{20} = Inv + M - Ene \tag{35}$$

where

Inv Investment cost for the summation of thermal solar collector

With tank price

M Maintenance Cost (when investment cost is 3%)

Ene Energy profit$\{(Annual\ solar\ heat\ collected) * (0.011)\}$

7.3.2 Optimal selection of two tanks and solar collector

The results of thermal solar system for three types of building presents in previous sections with control part. By the control equation (30), connected case considers and it compares with the non-connected case. Connected case is, when two-tank model assumes as the one tank system and get the balance equation between them. Non-connected case is simple the sum of heat demand for the domestic hot water only tank and space heating only tank model without solar collector. The multi objective optimization carries out for minimizing the energy consumption of ground source heat pump and life cycle cost in light, medium and massive type of building.

The results for non-connected and connected cases shows in Figures 66 and 67 with Pareto Front.

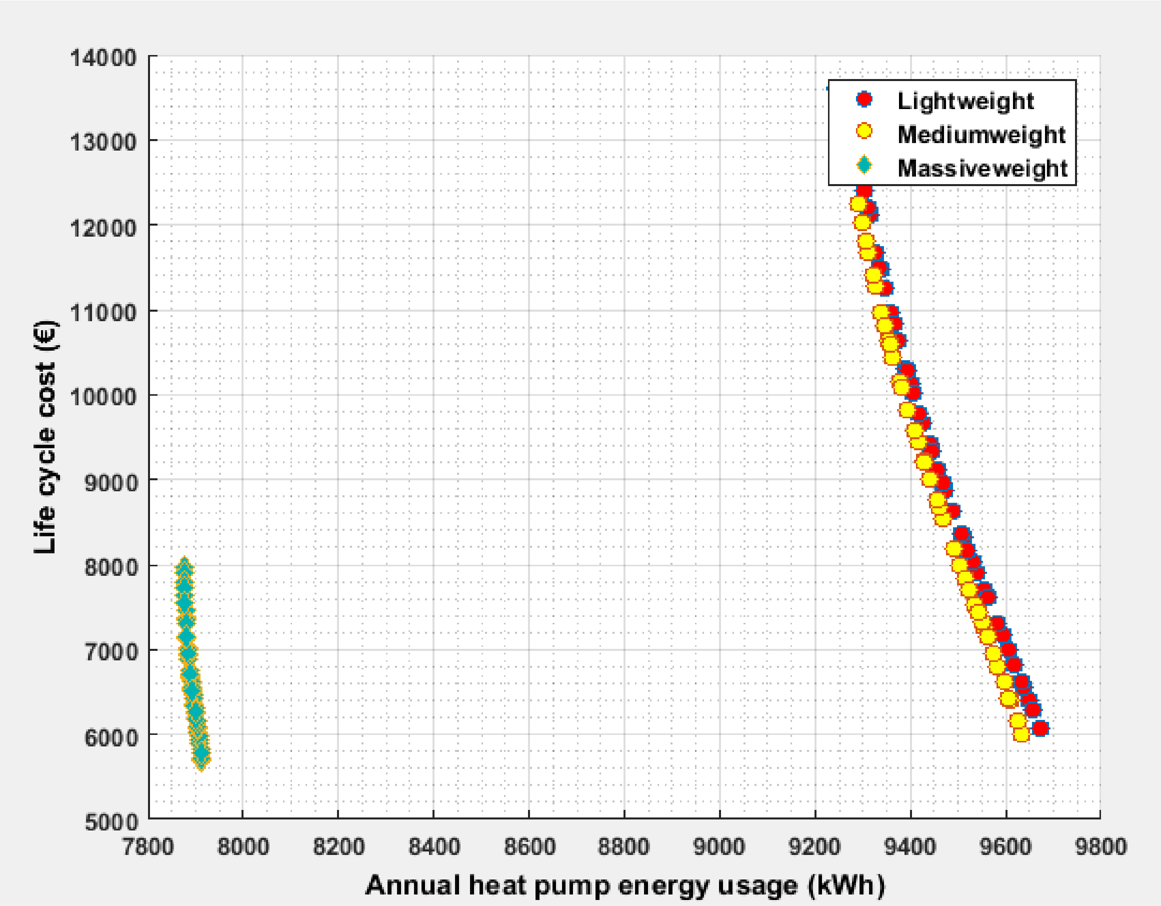


Figure 66. Pareto front for different types of building (Non-connected case)

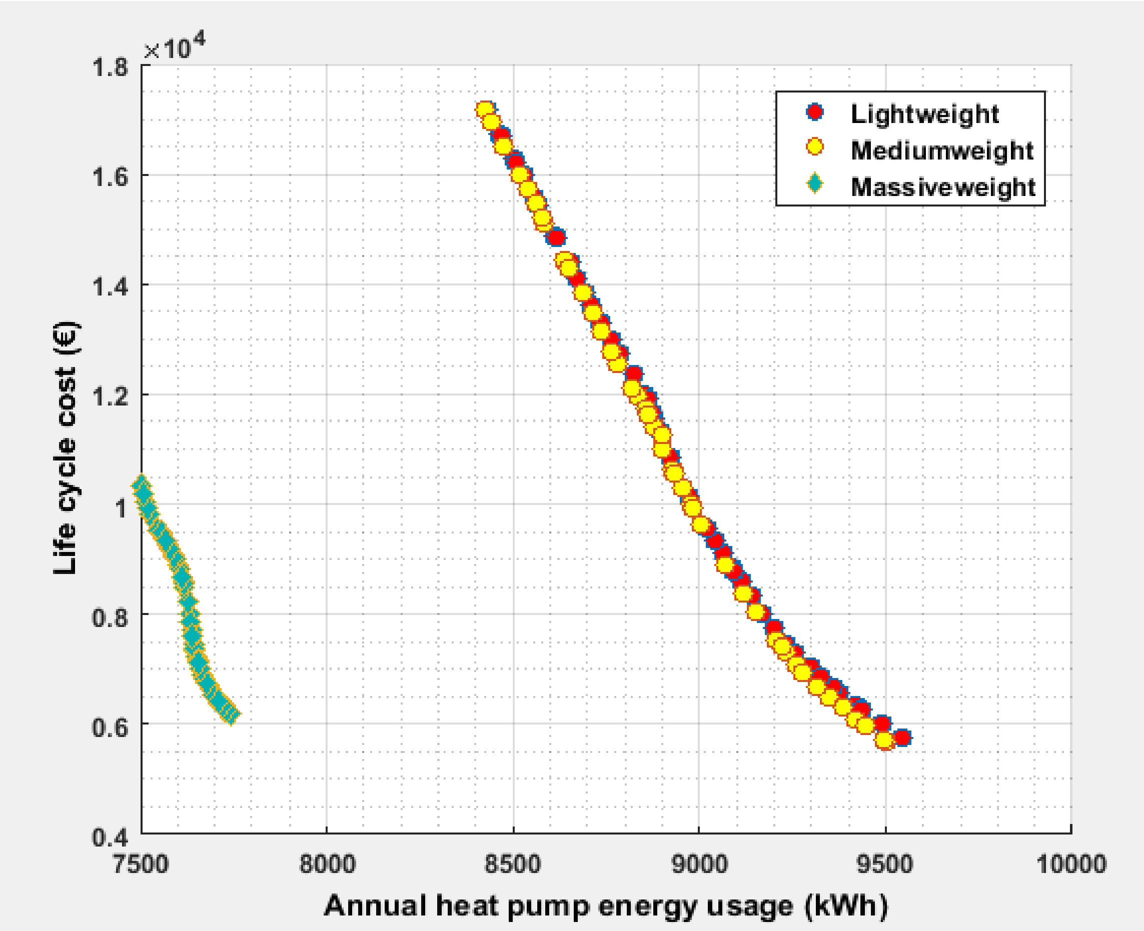


Figure 67. Pareto front for different types of building (Connected case)

The results show that the electricity consumption and cost of the system for massive type building is significantly lower in compared with two other building types. This trend is same in both states of connected and non-connected cases. Furthermore, connected case demonstrates the wide range of selection for the suitable solar collector and tank. It also shows higher energy efficiency compared with non-connected case. This shall discuss as effect of solar collector.

For studying the effect of economic parameters on optimal results, the interest rate changes from 3% to 9%. The effect of the varying the interest rate is studied on state of connecting two storage tanks for massive and lightweight buildings to check the significant differences. The results shows in figure 68 and 69.

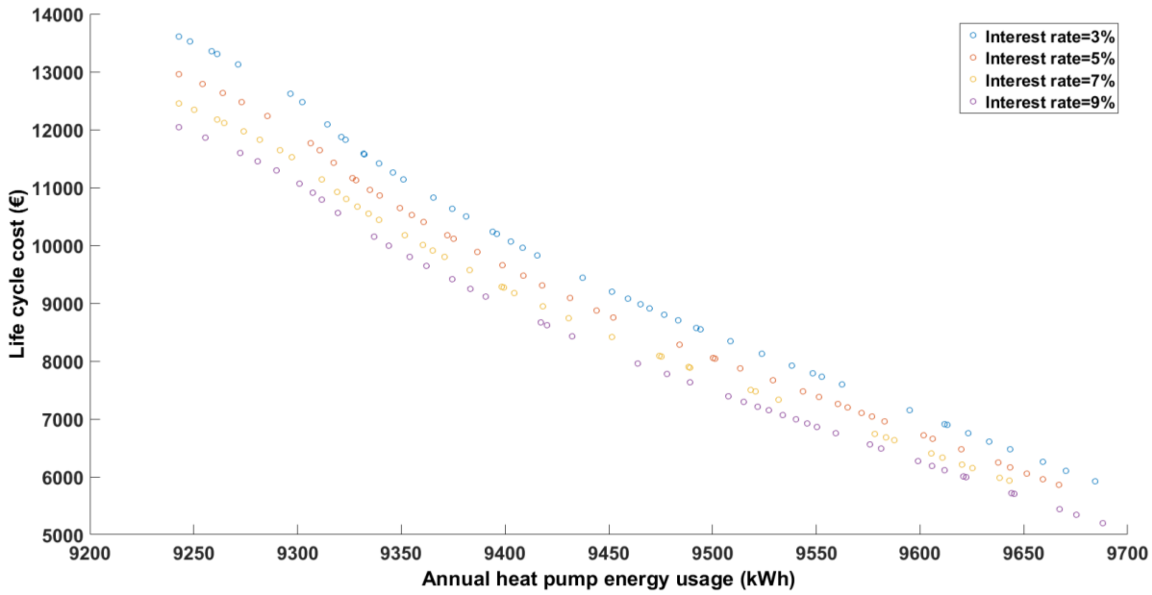


Figure 68. Life cycle cost result considering economic parameter in Light type building

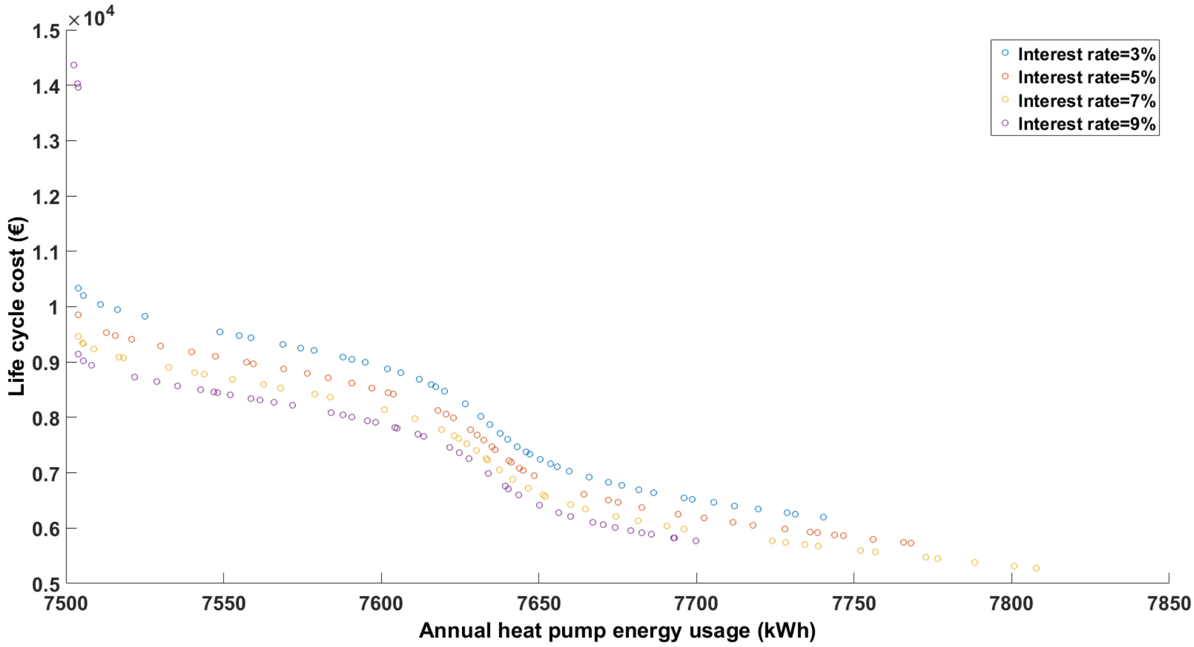


Figure 69. Life cycle cost result considering economic parameter in Massive type building

The results demonstrate that by increasing the interest rate, the life cycle cost reduces and system efficiency goes higher (less electricity usage). In case of massive building, the highest cost for optimal set is reduced about 10%, while the lightweight building case, the highest value for the life cycle cost dropped about 14% off.

The table 10 presents the optimal solutions for each case of buildings. The results belong to Pareto front for each case, which demonstrate in Figure 66 and Figure 67.

Light weight building						medium weight building						Massive weight building					
No connection			Connected			No connection			Connected			No connection			Connected		
HWST-DHW	HWST-SH	TSC	HWST-DHW	HWST-SH	TSC	HWST-DHW	HWST-SH	TSC	HWST-DHW	HWST-SH	TSC	HWST-DHW	HWST-SH	TSC	HWST-DHW	HWST-SH	TSC
0,5	0,5	1,76	0,5	0,5	1,06	0,50	0,50	1,62	0,50	0,50	10,00	0,50	0,50	1,14	0,50	0,50	3,60
0,5	2	10,00	0,5	0,5	1,06	0,50	2,00	10,00	0,50	0,50	10,00	0,50	0,50	6,30	0,50	0,50	1,21
0,5	2	10,00	0,5	0,5	10,00	0,50	2,00	10,00	0,50	0,50	1,49	0,50	0,50	6,30	0,50	0,50	1,21
0,5	0,5	3,66	0,5	0,5	10,00	0,50	1,00	8,24	0,50	0,50	1,49	0,50	0,50	2,07	0,50	0,50	3,60
0,5	0,5	5,67	0,5	0,5	2,53	0,50	2,00	8,37	0,50	0,50	3,30	0,50	0,50	4,64	0,50	0,50	2,18
0,5	0,5	6,32	0,5	0,5	3,93	0,50	2,00	8,97	0,50	0,50	5,32	0,50	0,50	2,26	0,50	0,50	2,88
0,5	0,5	4,14	0,5	0,5	4,32	0,50	0,50	1,84	0,50	0,50	2,53	0,50	0,50	1,15	0,50	0,50	2,98
0,5	0,5	2,64	0,5	0,5	9,20	0,50	1,00	8,80	0,50	0,50	7,17	0,50	0,50	6,01	0,50	0,50	1,89
0,5	2	8,82	0,5	0,5	6,55	0,50	0,50	5,05	0,50	0,50	4,25	0,50	0,50	2,68	0,50	0,50	3,28
0,5	0,5	4,27	0,5	0,5	8,69	0,50	0,50	2,36	0,50	0,50	3,72	0,50	0,50	4,25	0,50	0,50	1,79
0,5	1	6,97	0,5	0,5	9,54	0,50	0,50	3,93	0,50	0,50	6,45	0,50	0,50	2,44	0,50	0,50	3,12
0,5	1	8,82	0,5	0,5	6,14	0,50	2,00	9,35	0,50	0,50	4,52	0,50	0,50	2,16	0,50	0,50	1,96
0,5	1,5	9,21	0,5	0,5	7,91	0,50	0,50	1,84	0,50	0,50	2,76	0,50	0,50	1,38	0,50	0,50	3,39
0,5	2	9,75	0,5	0,5	3,68	0,50	0,50	3,74	0,50	0,50	8,04	0,50	0,50	1,31	0,50	0,50	2,45
0,5	1,5	8,55	0,5	0,5	1,93	0,50	0,50	5,31	0,50	0,50	3,72	0,50	0,50	4,42	0,50	0,50	1,34
0,5	1	6,41	0,5	0,5	2,74	0,50	0,50	6,69	0,50	0,50	9,02	0,50	0,50	1,92	0,50	0,50	2,82
0,5	1	8,82	0,5	0,5	3,48	0,50	0,50	4,73	0,50	0,50	2,20	0,50	0,50	1,79	0,50	0,50	2,12
0,5	0,5	4,81	0,5	0,5	7,54	0,50	2,00	9,55	0,50	0,50	2,89	0,50	0,50	5,57	0,50	0,50	1,29
0,5	1	8,04	0,5	0,5	5,73	0,50	0,50	2,67	0,50	0,50	3,21	0,50	0,50	5,50	0,50	0,50	2,63
0,5	0,5	2,06	0,5	0,5	2,11	0,50	0,50	5,51	0,50	0,50	6,02	0,50	0,50	5,43	0,50	0,50	1,82
0,5	0,5	9,25	0,5	0,5	2,94	0,50	0,50	2,36	0,50	0,50	1,76	0,50	0,50	5,67	0,50	0,50	2,26
0,5	1,5	9,46	0,5	0,5	7,32	0,50	2,00	7,92	0,50	0,50	7,80	0,50	0,50	5,03	0,50	0,50	1,74
0,5	0,5	2,27	0,5	0,5	6,94	0,50	1,00	6,78	0,50	0,50	2,20	0,50	0,50	4,74	0,50	0,50	1,68
0,5	0,5	5,26	0,5	0,5	5,40	0,50	1,00	6,13	0,50	0,50	8,63	0,50	0,50	1,53	0,50	0,50	1,40
0,5	1,5	8,35	0,5	0,5	4,50	0,50	0,50	4,58	0,50	0,50	9,67	0,50	0,50	5,37	0,50	0,50	2,02
0,5	1	6,73	0,5	0,5	3,21	0,50	1,50	8,10	0,50	0,50	4,56	0,50	0,50	4,40	0,50	0,50	1,59
0,5	1	9,03	0,5	0,5	9,03	0,50	2,00	9,00	0,50	0,50	7,35	0,50	0,50	1,77	0,50	0,50	1,49
0,5	1	8,04	0,5	0,5	8,38	0,50	2,00	8,24	0,50	0,50	3,91	0,50	0,50	1,47	0,50	0,50	1,66
0,5	2	9,38	0,5	0,5	7,18	0,50	0,50	4,25	0,50	0,50	6,94	0,50	0,50	3,71	0,50	0,50	2,00
0,5	2	9,38	0,5	0,5	1,23	0,50	0,50	2,94	0,50	0,50	2,05	0,50	0,50	5,82	0,50	0,50	1,86
0,5	0,5	4,62	0,5	0,5	1,58	0,50	1,00	5,69	0,50	0,50	8,42	0,50	0,50	4,09	0,50	0,50	2,06
0,5	1,5	8,89	0,5	0,5	1,72	0,50	0,50	4,24	0,50	0,50	8,78	0,50	0,50	2,57	0,50	0,50	1,53
0,5	0,5	3,30	0,5	0,5	5,19	0,50	1,00	7,25	0,50	0,50	4,75	0,50	0,50	2,88	0,50	0,50	1,72
0,5	1	7,87	0,5	0,5	9,03	0,50	0,50	3,50	0,50	0,50	7,35	0,50	0,50	1,63	0,50	0,50	3,20

0,5	0,5	3,30	0,5	0,5	6,65	0,50	0,50	5,72	0,50	0,50	4,01	0,50	0,50	3,29	0,50	0,50	1,55
0,5	1,5	8,82	0,5	0,5	2,21	0,50	0,50	7,03	0,50	0,50	4,97	0,50	0,50	3,97	0,50	0,50	2,69
0,5	0,5	2,11	0,5	0,5	1,52	0,50	0,50	6,13	0,50	0,50	5,46	0,50	0,50	2,88	0,50	0,50	1,97
0,5	1	7,22	0,5	0,5	4,78	0,50	0,50	2,52	0,50	0,50	5,77	0,50	0,50	1,47	0,50	0,50	2,77
0,5	1	7,64	0,5	0,5	9,65	0,50	0,50	3,50	0,50	0,50	4,97	0,50	0,50	1,93	0,50	0,50	2,54
0,5	0,5	3,08	0,5	0,5	7,48	0,50	0,50	3,18	0,50	0,50	3,01	0,50	0,50	4,95	0,50	0,50	2,54
0,5	2	8,98	0,5	0,5	5,52	0,50	0,50	3,18	0,50	0,50	6,82	0,50	0,50	3,89	0,50	0,50	1,44
0,5	0,5	2,40	0,5	0,5	8,17	0,50	0,50	5,83	0,50	0,50	9,77	0,50	0,50	5,92	0,50	0,50	1,44
0,5	0,5	1,83	0,5	0,5	1,25	0,50	1,00	7,93	0,50	0,50	7,70	0,50	0,50	3,16	0,50	0,50	1,37
0,5	2	8,98	0,5	0,5	8,03	0,50	1,50	7,91	0,50	0,50	1,77	0,50	0,50	1,68	0,50	0,50	2,42
0,5	0,5	6,47	0,5	0,5	3,36	0,50	0,50	2,97	0,50	0,50	9,36	0,50	0,50	1,31	0,50	0,50	1,22
0,5	0,5	7,69	0,5	0,5	5,25	0,50	1,00	7,41	0,50	0,50	6,66	0,50	0,50	3,01	0,50	0,50	3,21
0,5	0,5	2,40	0,5	0,5	4,94	0,50	1,50	8,41	0,50	0,50	6,66	0,50	0,50	5,89	0,50	0,50	2,25
0,5	0,5	2,86	0,5	0,5	5,94	0,50	1,50	8,60	0,50	0,50	6,15	0,50	0,50	5,13	0,50	0,50	2,60
0,5	0,5	6,61	0,5	0,5	5,94	0,50	0,50	6,40	0,50	0,50	9,20	0,50	0,50	1,56	0,50	0,50	2,10
0,5	0,5	5,05	0,5	0,5	1,52	0,50	1,00	6,62	0,50	0,50	5,61	0,50	0,50	4,83	0,50	0,50	3,05

Table 10. Optimal solutions for decision variables in different type of buildings

By reviewing the results, it can be seen that the maximum size of thermal solar collector for massive buildings never go higher than 7 m^2 while the size of thermal solar collector for light weight and medium weight meet the upper boundary as 10 m^2. Also for non-connected state, the size of the tanks for all members of Pareto front achieves as 0.5 m^3 as minimum defined size. Moreover, in connected state, the size of the tanks for two case of light and medium weight buildings vary between 0.5 m^3 to 2 m^3 while for massive type the size of the tanks converges to 0.5 m^3. In better words based on defined boundaries for the optimization, it can understand that in massive type, the system can arrange with lower size of thermal solar collector as well.

8. Conclusion

In the light, medium and massive type of building, two storage tanks with two geothermal heat pumps and solar collector model demonstrates. For the high efficient building model, energy system of components develop with simulation software and optimization codes. Two thermal tank models studies for responding the domestic hot water supply and the space heating radiation. Two different connection for the control conducts with the balance equation. Artificial neural network method uses for connecting two-tank model for the optimization. All 48 samples employ in one type of building and the 144 samples for the whole type of different insulated houses.

Multi objective optimization does with two objective functions, one is life cycle cost with the duration of 20 years and the other is heat pump electricity usage. The goal of this thesis is to reduce the heat pump electricity consumption and the components cost together considering the economic parameter with interest rate.

For the optimization, it occurs the heat collected by thermal solar collector and energy consumption of the ground source heat pump by using the neural networks. Neural network is typical consisting multiple layers to connect from input and output vectors with activation functions. It predefines input and output layer vectors according to number of decision variables as size of thermal solar collector and volume of the tank works. IDA-ICE implements to generate reference data for performance of energy system for each type of the buildings. The results of developed neural networks compare with the reference data as MOBO and they show good agreement with each other. Moreover, for showing the validity of using neural network in optimization, one test case optimization runs for a medium weight building with one storage tank. The results of optimization of the test case compares with optimization output from linking MOBO and IDA-ICE. The comparison reveals reliability of neural network in optimization and saving the time of calculation.

After validation the method of optimization, the developed neural networks uses in NSGAII method to find the optimal set of solution for energy system in each type of the buildings. The decision variables defines as size of hot water storage tanks and area of solar collector. In addition, for investigating the effect of economic parameters, the optimization for lightweight and massive building in connecting state repeats by changing the nominal interest rate.

From reviewing, the main outcomes can mention as follow

-. The neural network successfully applies for optimization to save the time duration of calculation and get the exact solution.

-. For increasing the accuracy of the neural network, it is better to develop the network models for simulating the thermal solar heat collecting and heat pump energy consumption separately.

-. The total calculation time for making the neural network model with Matlab and IDA simulation is about 14 hours while the optimization with IDA-ICE and MOBO takes almost 36 hours.

-. The massive type of building has the least and most effective energy system because of lower level of energy consumption in compared with two other types of buildings.

-. In non-connected state, the size of tanks in all types of buildings converged to minimum defined size as 0.5 m^3. The size of solar collector in non -connected state is higher for lightweight and medium weight buildings.

-. In connected state the efficiency of energy system and life cycle cost for all buildings types are improved. In connected state, the optimal size of warm tank is bigger than hot tank. It is because of using of warm tanks for two targets as responding to space heating demand and pre heating the hot tank.

-. Electricity price is fixed and only component costs considers to make the optimal selection.

-. Different interest rates considering various economic parameters for the LCC calculation demonstrates that by increasing the nominal interest rate, the feasibility of optimal solution increases.

-. More than one tank model can easily apply to the IDA simulation using balance equation.

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Appendixes

Appendix 1. Detailed descriptions of the structure materials and characteristic features

Appendix 2. Technical specifications of the ground source heat pump systems used in simulations

Appendix 3. Technical specifications of the solar thermal system used in the simulations.

Appendix 4. Technical descriptions of the energy system model in the IDA-ICE ESBO plant.

Appendix 5. Life Cycle Cost analysis used in the optimization result.

Appendix 1. Detailed descriptions of the structure materials and characteristic features

Light Weight Building

External wall (LW2010)

	Structure	D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Gypsum (s)	0.013	0.22	970	1090	0.059
2	Frame cc600	0.247	0.044	56	1720	5.614
3	Wind Shield Board (s)	0.009	0.22	970	1090	0.041
Total	**U-value**	**0.17 W/m²K**				

Internal wall (LW)

	Structure	D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Gypsum (s)	0.013	0.22	970	1090	0.059
2	Frame cc600	0.05	0.044	56	1720	1.137
3	Gypsum (s)	0.013	0.22	970	1090	0.059
Total	**U-value**	**0.702 W/m²K**				

Internal Floors (LW)

	Structure	D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Parquet (s)	0.015	0.14	460	2300	0.107
2	Particle board (s)	0.022	0.13	1000	1300	0.169
3	Frame cc600	0.1	0.044	56	1720	2.273
4	Gypsum (s)	0.013	0.22	970	1090	0.059
Total	**U-value**	**0.3599 W/m²K**				

Roof (LW2010)

	Structure	D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Mineral Wool	0.264	0.035	20	750	7.543
2	Frame cc600	0.15	0.044	56	1720	3.409
3	Gypsum (s)	0.013	0.22	970	1090	0.059
Total	**U-value**	**0.08944 W/m²K**				

External Floor (LW2010)

	Structure	D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Parquet	0.014	0.14	460	2300	0.1
2	Frame cc600	0.475	0.044	56	1720	10.795
3	Wind shield board (s)	0.009	0.22	970	1090	0.041
Total	**U-value**	**0.09004 W/m²K**				

Medium Weight Building

External wall (M2010)

	Structure	D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Lightweight concrete (s)	0.13	0.24	650	1000	0.542
2	Polyurethane thermal	0.24	0.05	70	1500	4.8
3	Lightweight concrete (s)	0.09	0.24	650	1000	0.375
Total	**U-value**	**0.1699 W/m²K**				

Internal wall (M)

	Structure	D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Lightweight concrete (s)	0.1	0.24	650	1000	0.417
Total	**U-value**	**1.705 W/m²K**				

Internal Floors (M)

	Structure	D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Parquet (s)	0.015	0.14	460	2300	0.107
2	Lightweight concrete (s)	0.015	0.135	500	100	0.111
3	Concrete (s)	0.1	1.7	2300	880	0.059
4	Filler (s)	0.005	0.9	1700	1000	0.0056
Total	**U-value**	**2.209 W/m²K**				

Roof (M2010)

	Structure	D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Mineral Wool (s1)	0.38	0.035	20	750	10.86
2	Concrete (s)	0.1	1.7	2300	880	0.059
3	Filler (s)	0.005	0.9	1700	1000	0.0056
Total	**U-value**	**0.09016 W/m²K**				

External Floor (M2010)

	Structure	D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Parquet	0.014	0.14	460	2300	0.1
2	Lightweight concrete (s)	0.015	0.135	500	100	0.111
3	Concrete (s)	0.1	1.7	2300	880	0.059
4	EPS thermal insulation (s)	0.425	0.04	20	750	10.625
Total	**U-value**	**0.09038 W/m²K**				

Massive Weight Building

External wall (MWPas)

Structure		D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Gypsum (s)	0.013	0.22	970	1090	0.059
2	Frame cc600	0.54	0.044	56	1720	12.27
3	Wind Shield Board (s)	0.009	0.22	970	1090	0.041
Total	**U-value**	**0.07973 W/m²K**				

Internal wall (LW)

Structure		D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Gypsum (s)	0.013	0.22	970	1090	0.059
2	Frame cc600	0.05	0.044	56	1720	1.137
3	Gypsum (s)	0.013	0.22	970	1090	0.059
Total	**U-value**	**0.702 W/m²K**				

Internal Floors (LW)

Structure		D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Parquet (s)	0.015	0.14	460	2300	0.107
2	Particle board (s)	0.022	0.13	1000	1300	0.169
3	Frame cc600	0.1	0.044	56	1720	2.273
4	Gypsum (s)	0.013	0.22	970	1090	0.059
Total	**U-value**	**0.3599 W/m²K**				

Roof (LWPas)

Structure		D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Mineral Wool	0.375	0.035	20	750	10.71
2	Frame cc600	0.15	0.044	56	1720	3.409
3	Gypsum (s)	0.013	0.22	970	1090	0.059
Total	**U-value**	**0.06967 W/m²K**				

External Floor (MWPas)

Structure		D, m	λ, W/mK	ρ, kg/m³	c_p, J/kgK	R, m²K/W
1	Parquet 14mm (s)	0.014	0.14	460	2300	0.1
2	Concrete (s)	0.08	1.7	2300	880	0.047
3	EPS thermal ins. (s)	0.485	0.04	20	750	12.125
Total	**U-value**	**0.08037 W/m²K**				

Appendix 2. Technical specifications of the ground source heat pump systems used in simulations

Table A2.1. Technical specifications of the borehole for installing ground source heat pump

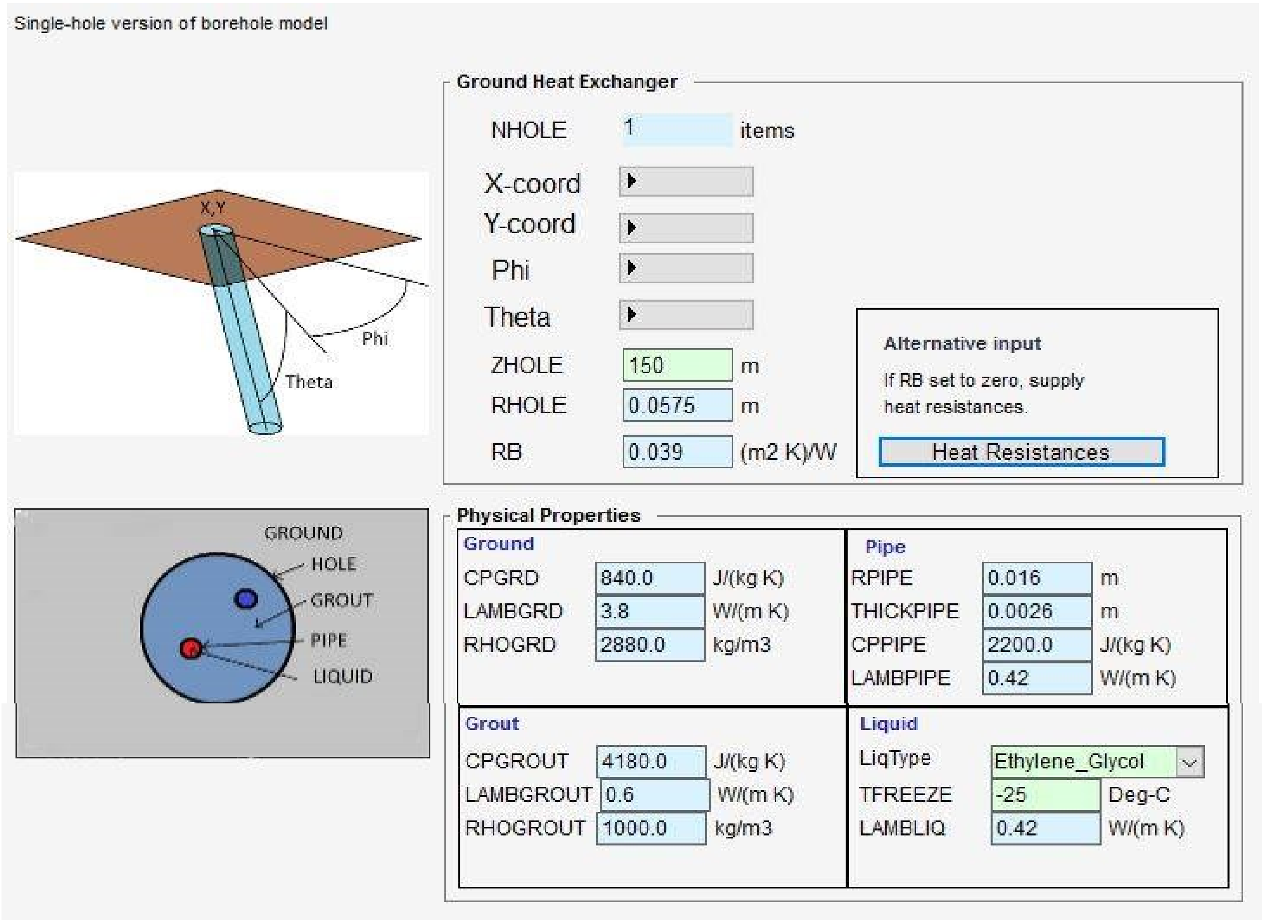


Table A2.2. Technical specifications of the NIBE F1345 heat pump system (Nibe 2014).

TEKNISET TIEDOT

CE IP 21

Tyyppi		24	30	40	60
Tehotiedot nimellisvirtauksella EN 255 mukaan [illegible]					
0/35					
Antoteho	kW	23,2	31,3	40,0	57,8
Jäähdytysteho	kW	18,4	24,6	31,8	45,1
Sähköteho	kW	4,84	6,67	8,17	12,7
COP	-	4,79	4,69	4,89	4,55
0/50					
Antoteho	kW	22,0	30,4	38,7	54,8
Jäähdytysteho	kW	15,6	21,6	28,0	38,4
Sähköteho	kW	6,41	8,80	10,6	16,4
COP	-	3,43	3,46	3,63	3,34
Tehotiedot EN 14511 mukaan					
0/35					
Antoteho (P_H)	kW	22,5	30,7	40,0	57,7
Sähköteho (P_E)	kW	5,05	7,00	8,88	14,1
$COP_{EN14511}$	-	4,42	4,36	4,51	4,10
0/45					
Antoteho (P_H)	kW	21,5	30,1	39,0	55,1
Sähköteho (P_E)	kW	6,08	8,47	10,6	16,5
$COP_{EN14511}$		3,50	3,53	3,68	3,35
10/35					
Antoteho (P_H)	kW	30,1	40,3	51,8	78,2
Sähköteho (P_E)	kW	5,39	7,80	9,70	16,1
$COP_{EN14511}$	-	5,54	5,15	5,32	4,84
10/45					
Antoteho (P_H)	kW	28,7	39,5	50,9	72,7
Sähköteho (P_E)	kW	6,44	9,25	11,7	18,4
$COP_{EN14511}$		4,43	4,24	4,34	3,95
Sähkötiedot					
Nimellisjännite		400V 3NAC 50 Hz			
Maks. käyttövirta, lämpöpumppu [2]	A_{rms}	19,4	24,8	30,9	47,1
Maks. käyttövirta, kompressori	A_{rms}	7,8	10,5	13,9	19,9
Suositeltu varokekoko	A	25	30	35	50
Käynnistysvirta	A_{rms}	29	34	42	53
Suurin sallittu impedanssi liitäntäpisteessä [1]	ohmia	-	-	-	0,4
Teho, LK-pumppu [2]	W	10 - 370	10 - 370	735 - 890	1150 - 1290
Teho, kiertopumppu	W	5 - 174	5 - 174	5 - 174	5 - 174
IP-luokka		IP 21			
Kylmäainepiiri					
Kylmäaineen tyyppi		R407C			R410A
Täytösmäärä	kg	2 x 2,2	2 x 2,3	2 x 2,4	2 x 2,4
Katkaisuarvo, korkeapainepressostaatti	baaria	32			42
Ero, korkeapainepressostaatti	baaria	-7			
Katkaisuarvo, matalapainepressostaatti	baaria	0,8			2
Ero, matalapainepressostaatti	baaria	0,7			
Katkaisuarvo, matalapainepressostaatti (ilman AMB 30)	baaria	1,3			3,5
Katkaisuarvo, matalapainepressostaatti (AMB 30:n kanssa)	baaria	0,8			2
Ero, matalapainepressostaatti	baaria	0,1			

Table A2.3. Technical specifications of the NIBE F2300 heat pump system (Nibe 2014).

TEKNISET TIEDOT

CE IP24

3x400V			F2300-14	F2300 -20
Tehotiedot nimellisvirtauksella [1]				
15/55	Antoteho / ottoteho /COP	kW/kW/-	17,0/4,49/3,79	23,6/6,43/3,68
7/35	Antoteho / ottoteho /COP	kW/kW/-	14,1/2,96/4,77	19,6/4,22/4,63
2/45	Antoteho / ottoteho /COP	kW/kW/-	13,1/3,58/3,63	17,9/5,11/3,49
-7/45	Antoteho / ottoteho /COP	kW/kW/-	10,7/3,50/3,06	14,6/4,92/2,96
-7/55	Antoteho / ottoteho /COP	kW/kW/-	11,0/4,24/2,59	15,2/5,95/2,55
-15/55	Antoteho / ottoteho /COP	kW/kW/-	9,16/4,11/2,23	12,7/5,69/2,23
Tehotiedot EN14511 [2] **mukaan**				
10/35	Antoteho / ottoteho	kW/kW/-	15,49/3,20/4,84	20,85/4,47/4,66
7/35	Antoteho / ottoteho	kW/kW/-	13,8/3,14/4,39	17,7/4,37/4,04
7/45	Antoteho / ottoteho	kW/kW/-	14,1/3,83/3,69	18,3/5,38/3,41
7/55	Antoteho / ottoteho	kW/kW/-	15,22/4,78/3,18	19,04/6,55/2,91
2/35	Antoteho / ottoteho	kW/kW/-	11,84/3,08/3,84	15,46/4,38/3,53
2/45	Antoteho / ottoteho	kW/kW/-	12,27/3,74/3,28	15,95/5,28/3,02
-7/35	Antoteho / ottoteho	kW/kW/-	9,41/3,03/3,10	12,83/4,32/2,97
-7/45	Antoteho / ottoteho	kW/kW/-	9,72/3,66/2,65	13,28/5,15/2,58
-15/35	Antoteho / ottoteho	kW/kW/-	7,49/2,96/2,53	10,37/4,2/2,47
-15/45	Antoteho / ottoteho	kW/kW/-	7,74/3,52/2,20	10,73/4,97/2,16
Sähkötiedot				
Käyttöjännite			400V 3NAC 50 Hz	
Suurin virrankulutus, lämpöpumppu		A(rms)	12	16
Suurin virrankulutus, kompressori		A(rms)	8,2	12,8
Käynnistysvirta		A(rms)	30	39,6
Suurin sallittu impedanssi kytkentäpisteessä [3]		Ohm	-	-
Varoke		A(rms)	16	16
Kylmäainepiiri				
Kylmäaine			R407C	
Kompressori			Kierukka	
Tilavuus		kg	2,2	2,8
Lämmitysneste				
Min/maks. järjestelmäpaine, lämmitysneste		MPa	0.05/0.3 (0.5/3 bar)	
Min/maks. virtaus		l/s	0,33/0,67	0,47/0,94
Nimellisvirtaus [4]		l/s	0,33	0,47
Sisäinen painehäviö nimellisvirtauksella		kPa	4,5	4,5
Lämmitysnesteen maks./min lämpötilan jatkuvassa käytössä		°C	65/25	
Lämmitysnesteliitäntä uros		mm	G1 1/4" (Ø35mm)	

Äänenpainetasot

F2300 sijoitetaan yleensä seinän viereen, tästä johtuva äänen suunnattu leviäminen ympäristöön tulisi ottaa huomioon. Pyri siksi löytämään paikka, jossa ääni ei häiritse naapureita.

Äänenpainetasoon vaikuttavat lisäksi seinät, maaperän korkeuserot, jne., minkä vuoksi näitä arvoja tulisi pitää ohjeellisina.

F2300 toimii kesällä pienellä puhallinnopeudella ja muina aikoina suurella puhallinnopeudella.

Tyyppi		F2300-14		F2300-20	
Äänitehotaso, standardin EN12102 mukaan lämpötiloilla 7/45	Lw(A)	50/62		53/62	
Puhallinnopeus		**Pieni**	**Suuri**	**Pieni**	**Suuri**
Suurin äänenpainetaso 2 metrin etäisyydellä*	dB(A)	36	48	39	48
Suurin äänenpainetaso 6 metrin etäisyydellä*	dB(A)	26.5	38.5	29.5	38.5
Suurin äänenpainetaso 1 0 metrin etäisyydellä*	dB(A)	22	34	25	34

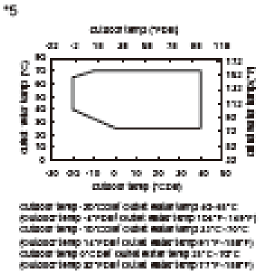
* Vapaakenttä

Table A2.4. Technical specifications of the Mitsubishi CAHV P500YA-HPB heat pump system (Mitsubishi electric).

Model			CAHV-P500YA-HPB (-BS)
Power Source			3-phase 4-wire 380-400-415V 50/60Hz
Capacity *1		kW	45
		kcal/h	38,700
		BTU/h	153,540
	Power input	kW	12.9
	Current input	A	21.78-20.69-19.94
	COP (kW / kW)		3.49
Capacity *2		kW	45
		kcal/h	38,700
		BTU/h	153,540
	Power input	kW	10.9
	Current input	A	10.6 (400V)
	COP (kW / kW)		4.13
Capacity *3		kW	45
		kcal/h	38,700
		BTU/h	153,540
	Power input	kW	25.6
	Current input	A	43.17-41.01-39.53
	COP (kW / kW)		1.76
Maximum current input *4		A	57.77-54.88-52.90
Water pressure drop *1			12.9kPa (1.87psi)
Temp. range	Outlet water temp *5		25~70°C 77~158°F
	Outdoor temp *5	D.B	-20~40°C -4~104°F
Circulating water volume range			7.5 m³/h - 15.0m³/h
Sound Pressure level (measured in anechoic room) *1 at 1m		dB (A)	59
Sound Pressure level (measured in anechoic room) *1 at 10m		dB (A)	51
Sound Pressure level (measured in anechoic room) *4		dB (A)	63
Diameter of water pipe	Inlet	mm (in)	38.1 (Rc 1 1/2") screw
	Outlet	mm (in)	38.1 (Rc 1 1/2") screw
External finish			Acrylic painted steel plate <MUNSELL 5Y 8/1 or similar>
External dimension H × W × D		mm in.	1,710 (without legs 1,650) × 1,978 × 759 67.3 (without legs 65.0) × 77.9 × 29.9
Net weight		kg (lb)	526 (1,160)
Accessories			Y strainer Rc 1 1/2
Design Pressure	R407C	MPa	3.85
	Water	MPa	1.0
Drawing	Wiring		KC94G265X01
	External		KC94G195X01
Heat exchanger	Water side		stainless steel plate and copper brazing
	Air side		Plate fin and copper tube
Compressor	Type		Inverter scroll hermetic compressor
	Manufacture		MITSUBISHI ELECTRIC CORPORATION
	Starting method		Inverter
	Motor output	kW	7.5 × 2
	Case heater	kW	0.045 × 2
	Lubricant		MEL32
FAN	Air flow rate	m³/min	185 × 2
		L/s	3,083 × 2
		cfm	6,532 × 2
	External static press.		0Pa (0mmH$_2$O)
	Type × Quantity		Propeller fan × 2
	Control, Driving mechanism		Inverter-control, Direct-driven by motor
	Motor output	kW	0.46 × 2
HIC circuit (HIC:Heat inter-Changer)			Copper pipe
Protection	High pressure protection		High pres.Sensor & High pres.Switch at 3.85MPa (643psi)
	Inverter circuit		Over-heat protection, Over current protection
	Compressor		Over-heat protection
	Fan motor		Thermal switch
Defrosting method			Auto-defrost mode (Reversed refrigerant circle)
Refrigerant	Type × original charge		R407C × 5.5(kg) × 2
	Control		LEV and HIC circuit

*1 Under Normal heating conditions at outdoor temp. 7°CDB/6°CWB(44.6°FDB/42.8°FWB)/ outlet water temp 45°C(113°F), inlet water temp 40°C(104°F).
*2 Under Normal heating conditions at outdoor temp. 7°CDB/6°CWB(44.6°FDB/42.8°FWB)/ outlet water temp 35°C(95°F), inlet water temp 30°C(86°F).
*3 Under Heating conditions at outdoor temp. 7°CDB/6°CWB(44.6°FDB/42.8°FWB), outlet water temp 70°C (158°F).
*4 Under Heating conditions at outdoor temp. 7°CDB/6°CWB(44.6°FDB/42.8°FWB) when this unit is set to capacity priority mode by non-voltage B contact.
* Due to continuing improvement, the above specifications may be subject to change without notice.
* Please don't use the steel material for the water piping material.
* Please always make water circulate or pull out the circulation water completely when not using it.
* Please do not use groundwater and well water.
* Install the unit in an environment where the wet bulb temp. will not exceed 32°C.
* The water circuit must use the closed circuit.

*5



Unit converter
kcal = kW x 860
BTU/h = kW x 3,412
cfm = m³/min x 35.31
lb = kg/0.4536

Appendix 3. Technical specifications of the solar thermal system used in the simulations.

Table A3.1. Solar thermal system and its full technical specifications (Savosolar 2014b).

Specification	Description / Value
Make and model	Savosolar SF100-03-DS / SF100-03-DE flat plate collector, Full Al Direct Flow MPE Absorber
Type of construction	Flat Plate Solar Thermal Collector
Absorber type	Full Al Double Harp
External dimensions / collector	2057 x 1059 x 98 mm
Gross area / collector	2057 x 1059 mm^2 (2,18 m^2)
Aperture area / collector	2000 x 1001 mm^2
Absorber area / collector	2000 x 1001 mm^2
Efficiency	η_0 = 0,92, a_1 = 1,8 W/m^2 K, a_2 = 0,036 W/m^2 K
Stagnation temperature	176 °C
Incident angle modifier	K (50 °C) = 0,95
Absorber coating	MEMO 3 layer selective PVD coating
Absorptance	96 % +/- 2
Emissivity	5 +/- 2 %
Header tube	DS ϕ22 / DE ϕ18
Max. operating pressure	1000 kPa (10 bar)
Pressure drop	910 Pa @ 82 kg/h
Thermal insulation	50 mm mineral wool
Glass covering	Sunarc tempered solar safety AR glass
Solar transmittance of the glass / Thickness	96,1 % / 3,2 mm (AR)
Liquid content	1,9 liters
Weight empty	35 kg
Tilt angle	0-90° for rooftop and free standing setup

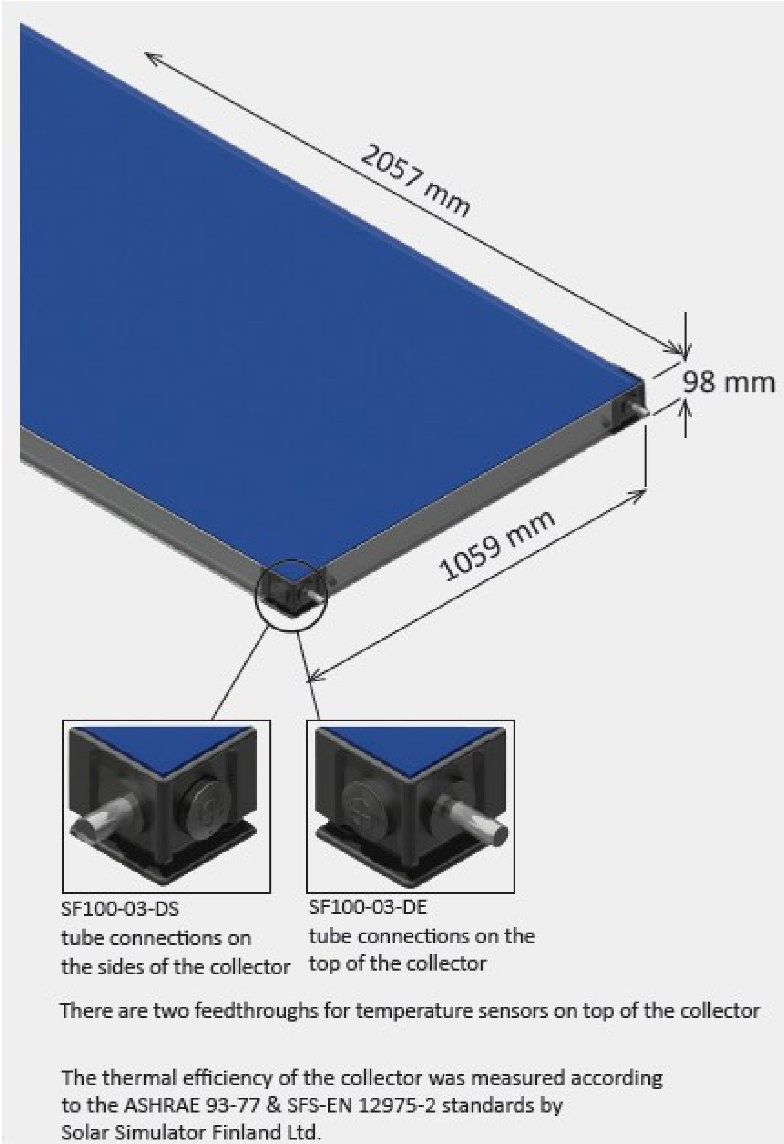


Figure A3.2. Dimensions of the solar thermal collectors (Savosolar 2014b).

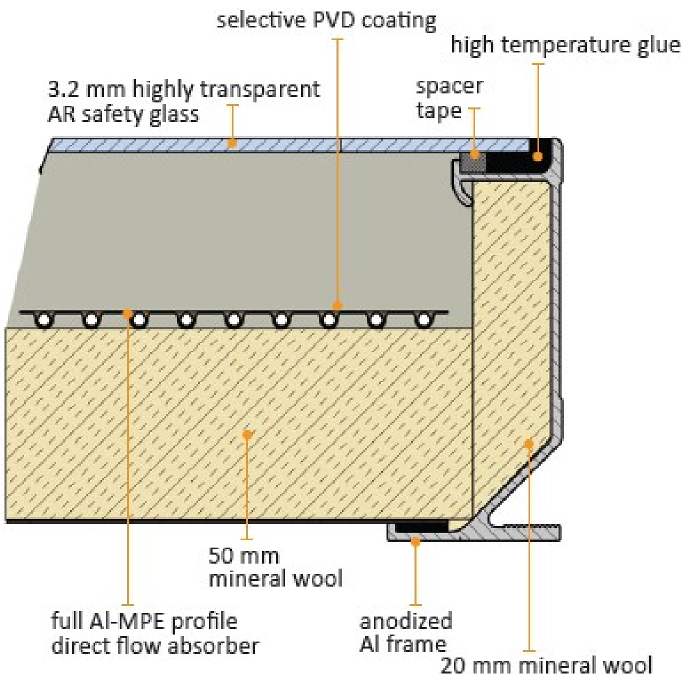


Figure A3.3. Construction of the solar thermal collectors (Savosolar 2014b).

Appendix 4. Technical descriptions of the energy system model in the IDA-ICE ESBO plant.

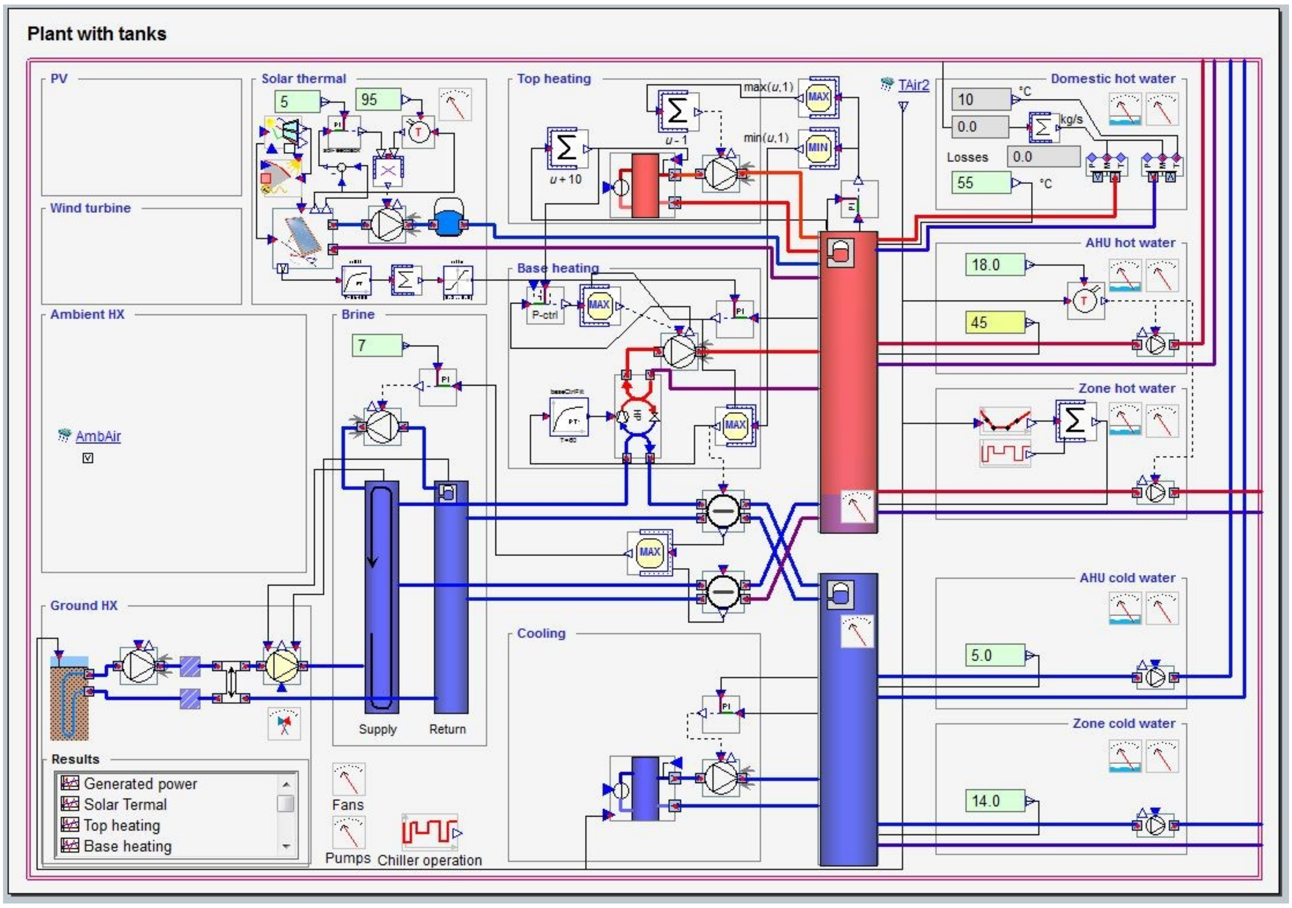


Figure A4.1. The ideal heat storage tank model in the IDA-ICE ESBO plant.

As Figure A4.1 demonstrates, layered stratified tank model connects to the space heating and domestic hot water supply in the ideal IDA simulation. Brine type reciprocating heat pump employs with auxiliary heating system as top heating. Temperature layer of the tank could have 50 amounts, showing temperature variation inside of IDA model. Generally, it creates one tank model adding solar thermal collector or photovoltaic. Domestic hot water supply tank average-temperature is 55°C while space heating offering temperature is around 45°C. Inside of tank, condensing temperature of the tank is highest at the top layer of the tank as 55-65 °C and bottom layer of the tank reaches 30-40 °C. Coefficient of performance is signified as 4 with reciprocating type ground source heat pump thus, heat exchanger is connected.

Appendix 5. Life Cycle Cost analysis used in the optimization result.

Table A5.1 Electricity price based on information of 2012 by HVAC research team in Aalto Univ.

Finish VAT	Electricity tax (c/kWh)	Company margin (c/kWh)	Distribution cost (c/kWh)	Feed-in tariff (c/kWh)
24%	2.79372	0.3	3.98	8.35

Table A5.2 Price of the hot water storage tank

Height (m)	Diameter (m)	Volume (m3)	Price (€)	Unit price (€/m3)
2.050	0.650	0.68	1819.00	2675.36
2.050	0.800	1.03	2199.00	2135.12
2.050	0.950	1.45	2305.00	1587.09
2.100	1.050	1.82	2579.00	1419.00
2.150	1.250	2.64	3285.00	1245.68
2.250	1.400	3.46	3649.00	1054.06
2.250	1.500	3.97	3339.00	840.20
2.300	1.600	4.62	3539.00	765.67
2.350	1.800	5.98	4799.00	802.91